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DESIGN CONSIDERATIONS FOR A PILOT PROCESS FOR SEPARATING MUNICIPAL REFUSE

David Gordon Wilson, et al

Massachusetts Institute of Technology

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NATIONAL ENVIRONMENTAL RESEARCH CENTER
OFFICE OF RESEARCH AND DEVELOPMENT
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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

In this innovative and forward-thinking study, the researchers have approached a new way of looking at municipal solid waste categorization and mechanical separation. The classical techniques of expensive grinding and mechanically sorting into component material types were challenged and compared with the potential advantages of several new separation schemes. The research recommends that such new systems be further refined and tested on a pilot or field scale.

A. W. Breidenbach, Ph.D.
Director
National Environmental
Research Center, Cincinnati

ABSTRACT

Separating municipal solid waste into its valuable and recycleable elemental components is examined here in terms of various mechanical engineering schemes and processes that might best accomplish this task. Although past efforts have concentrated on first reducing the particle size by shredding, this investigation considered the advantages of whole-item coding and sorting without the expensive shredding operation. The result was an interesting base technology for a proposed pilot plant design that could potentially redirect future resource recovery efforts in solid waste.

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CHAPTER 1

INTRODUCTION

PROCESS OUTLINE AND SPECIAL FEATURES

The M.I.T. approach to the problem of separating mixed municipal refuse differs from other developments of automated plants in several ways.

1. As much separation as is economically justifiable is carried out with refuse in the as-received condition. Only certain non-homogeneous items are comminuted (shredded, pulverized, hammermilled, or ground). In other mechanized processes, all incoming refuse is comminuted or pulped before being processed in bulk.

2. The individual (larger) pieces of refuse which are clean and otherwise undistorted are scanned by a number of sensors in series, with data from each sensor being fed to a minicomputer. A decision about the allocation of each individual item to a category is not made until all sensors have recorded data. Subsequently, the refuse item can be allocated to one of a large number, perhaps 25, categories. In contrast, most other sorting operations carry out a series of successive binary sorts into a limited number of predetermined categories.

3. The sorting performance of the plant can be modified by changes in computer instructions from day to day. The plant manager can thereby respond to changing market conditions.

4. Pieces of refuse below a chosen size, including pieces from the comminuted heterogeneous refuse, are taken to a new type of multiple-output vortex classifier in which the refuse is sorted by density.

POTENTIAL ADVANTAGES AND DISADVANTAGES

Potential advantages

1. The values available in municipal refuse are maximized if the refuse is maintained in an as-received condition. This is particularly true in the cases of paper products and glass. Clean, bundled newspaper and telephone books

can be collected and discharged from the compaction truck virtually uncontaminated, but if they are then comminuted or pulped, the resulting mixture can lose a high proportion of its potential value. Glass bottles are also mostly undegraded in compaction trucks. One of our studies - see chapter 2 - showed that over 90 percent of bottles collected in a compaction truck survived without breakage. There are two possible advantages in keeping bottles whole. One is that whole bottles, whether "unreturnable" or not, may be sorted by brand and, if undamaged, may be cleaned and sold back to the bottlers. The second advantage of collecting whole bottles is that they may be easily sorted by color so that, if the bottles are not sold back to the bottlers, color-sorted cullet may be produced.

2. The performance of the plant may be adjusted day by day to suit market conditions.

3. It is comparatively easy and inexpensive to substitute or add new or improved sensors as they become available to improve the sorting performance where found to be necessary.

4. By keeping refuse in the as-received condition so far as is possible, all options remain open. Various components may be recombined or kept separated and pulped, comminuted, incinerated, pyrolized, hydrolyzed and so on. In some cases the plant might be regarded as a "front-end" device for other processes.

5. Except for the computer and sensors, the plant uses conventional hardware and technology and should be considerably lower in cost than, for instance, an incinerator of the same capacity. The computer required is a low-cost device, and the sensors will likewise be a very small proportion of total plant cost.

6. Energy requirements for the sorting process are much lower than for alternative processes, principally because of the absence of bulk comminution. Energy requirements for reuse of some of the products, eg bottles, will also be lower than if they were comminuted.

Potential disadvantages

1. The plant relies on mechanical devices to separate incoming refuse into individual pieces. The heterogeneity of refuse

is such that it is unlikely that any plant would be able to work completely automatically with refuse as input. Human oversight will be required, so that controls may be overridden when it seems necessary. Some of the components of refuse which traditionally give trouble are, for example, loose coils of rope or wire; large pieces of textiles such as stair carpets and rugs; and leaky containers of sticky or noxious materials. As these types of components cause problems in present refuse-treatment plants, the relative disadvantage which the present plant would experience might not be great. In other words, it is likely that all types of refuse-treatment plants will continue to require human oversight and occasional correction of the input feed.

REASONS FOR CHOICE OF PRESENT APPROACH

The primary difference in the present approach to the more usual methods of attempting automated separation is that comminuting of the input stream is not used. Comminution is usually carried out by hammermilling, but several other forms of comminution equipment have been used. [1] Comminution is costly in terms of first cost, energy costs (low at present but likely to increase markedly), supervisory costs, and maintenance costs, scheduled and unscheduled.[2] The added costs of size reduction by hammermilling are estimated to range from $2 per input ton to $10 per input ton, depending on the size of the plant and the fineness of the ground product required. Hammermilling equipment adds noise, dust, and some explosion danger (from gasoline cans, for instance).

In return for these costs, size reduction of municipal refuse conveys the very great advantage that the product approximates to a homogeneous mixture having properties which can be estimated fairly closely, and which can be subsequently handled and treated by equipment developed for bulk materials, for instance ore. We are trading this advantage for the savings in costs of size reduction and for the potential of greatly increased revenues from the process streams.

REVIEW OF ALTERNATIVE RECLAMATION PROCESSES

The principal alternative available processes for separating mixed municipal solid wastes are adequately described in a number

of publications.[3,4] We shall merely list the main categories here and indicate the characteristics of each. We are defining "separation" to exclude processes in which the chemical composition is modified, such as incineration, pyrolysis, hydrolysis, shift conversion and so forth.

Dry separation

Traditional plants for the separation of municipal refuse for recycling have involved hand picking of useful items either from a mass of dumped material, or, during the last few decades, from materials flowing past so-called "picking stations" on a moving belt. Darnay and Franklin have shown that such methods are uneconomic in present circumstances.[5]

Present proposals for dry separation generally involve comminution by hammermilling, followed by air classification, magnetic ferrous-metal extraction, and perhaps other binary sorters such as electrostatic devices and heavy-medial separators for inorganic materials and nonferrous metals. The U.S. Bureau of Mines[6] and the National Center for Resource Recovery[7] are presently (1973) testing or building dry-separation plants of this general type.

Wet separation

The Black Clawson Co. uses a modified "Hydropulper", developed for repulping secondary papers, for processing the entire municipal waste stream.[4] An impeller/breaker at the bottom of the Hydropulper pulps the organic materials and fractures or reduces in size most of the inorganic materials.

In the James F. Tracy refuse-reclamation process[8] incoming refuse, less large useful or damaging items which are removed by hand, is fed into a large, long rectangular tank, which is kept in the state of agitation. Inorganic materials fall to the bottom of the tank where they are removed from one end by means of a travelling drag conveyor. Floating organic materials are directed by water jets to the other end of the tank, where they are chopped and pulped. The inorganic materials are separated magnetically and the remainder, principally glass and nonferrous metals, is sorted by hand in so far as it is economically justified.

Separation of nonferrous metals

A stream of mixed nonferrous metals and the glass is a common factor in these plants and in auto shredders. Many approaches have been followed to extract as many values as possible from such a stream. Heavy-media separation has been mentioned; fluidized-bed separation has been developed;[4] magnetic so-called "ferrofluids," developed by the Avco Company, show promise;[9] and a group at Vanderbilt University under Professor Charles Roos has made a magnetic-induction separator.

None of these approaches yet appear to have attained general commercial success for small pieces (eg less than half-inch mesh) of mixed nonferrous materials.

REVIEW OF PAST M.I.T. WORK

The direction of the M.I.T. approach to resource recovery has changed somewhat during the four years of funding. It is worth reviewing the reasons for the changes of direction.

The original proposal suggested the adaptation of a air-vortex coal pulverizer which had recently been successfully developed at M.I.T. It was then proposed that the particles emerging from the pulverizer would be carried in high-velocity (eg 500 feet per second) air stream along a tube past a series of sensors. Switching of the particles would subsequently be accomplished fluidically.

This plan was abandoned during the first contract period[10] for two reasons. Firstly, the principle which worked so successfully with coal, a relatively friable material, was defeated by tough or stringy materials such as steel and textiles. Secondly, although a number of promising possibilities for sensors were identified (possibilities which have been developed to the present successful models) it was found that the fastest processing times would be far too long for the coding of particles moving at hundreds of feet per second to be feasible.

It was found, however, that a considerable degree of separation of materials took place downstream of the vortex pulverizer, as the materials flowed out into a radial diffuser. During an analysis of the flow conditions, the principle for the vortex classifier, in which air or water flows regularly inward in a vortex,was conceived.

A further input to the redirection of the work was provided by several visits to plants where manual separation of mixed

municipal refuse took place by hand picking from moving belts.[5] It was realized that, in general, only large items are hand picked in this way, and that there is considerable value in these large items. It therefore seemed to offer considerable advantages if the processing of large items could be automated rather than for these large items (for examples, bundles of telephone books, or glass bottles) to be comminuted into perhaps thousands of individual pieces and then for these pieces to be separated.

Accordingly, the new direction of the work was established and remains in force today.

The work on sensors, described by Smith,[11] narrowed down to one employing several wavelengths of infrared reflected off the surface of each piece of refuse; and one involving physical contact (of a small ball bearing carrying an accelerometer) with the items of refuse.

Meanwhile, a sub-project in mechanical handling was set up to present to the sensors one piece of refuse at a time. The device initially selected to perform this function was a compartmented carousel with stationary sensors located in one general area of the circumference and hoppers into which the items of refuse could be diverted. It was felt that the centrifugal action, and the predetermined velocity at which the sensors would strike the accelerator and pass the infrared sensor, would contribute to accuracy.

However, the problem of arranging that a sufficiently high proportion of the compartments had one, and only one, piece of refuse contained in each as it passed the sensors was found to be very difficult. This system could be called "open loop"; after a number of statistical tests had been made and alternative approaches had been reviewed, the decision was made to convert to a closed-loop, feedback, system.

The essentials of such a system are that items of refuse need to be separated one from another, so that a simple sensor can determine merely that an item of refuse is present. Subsequently that item can then be presented to coding sensors.

Of the many possibilities which were considered for the incorporation of this principle into an operating plant, the method chosen shown in figure 1, was to allow the larger pieces of refuse to drop from the end of a large-mesh vibrating screen. (Over the input end of this screen is a fan and moving belt to extract loose paper and plastic film, and a magnet and moving belt to remove ferrous items; and small pieces of refuse would pass through the screen for alternative treatment). Below the

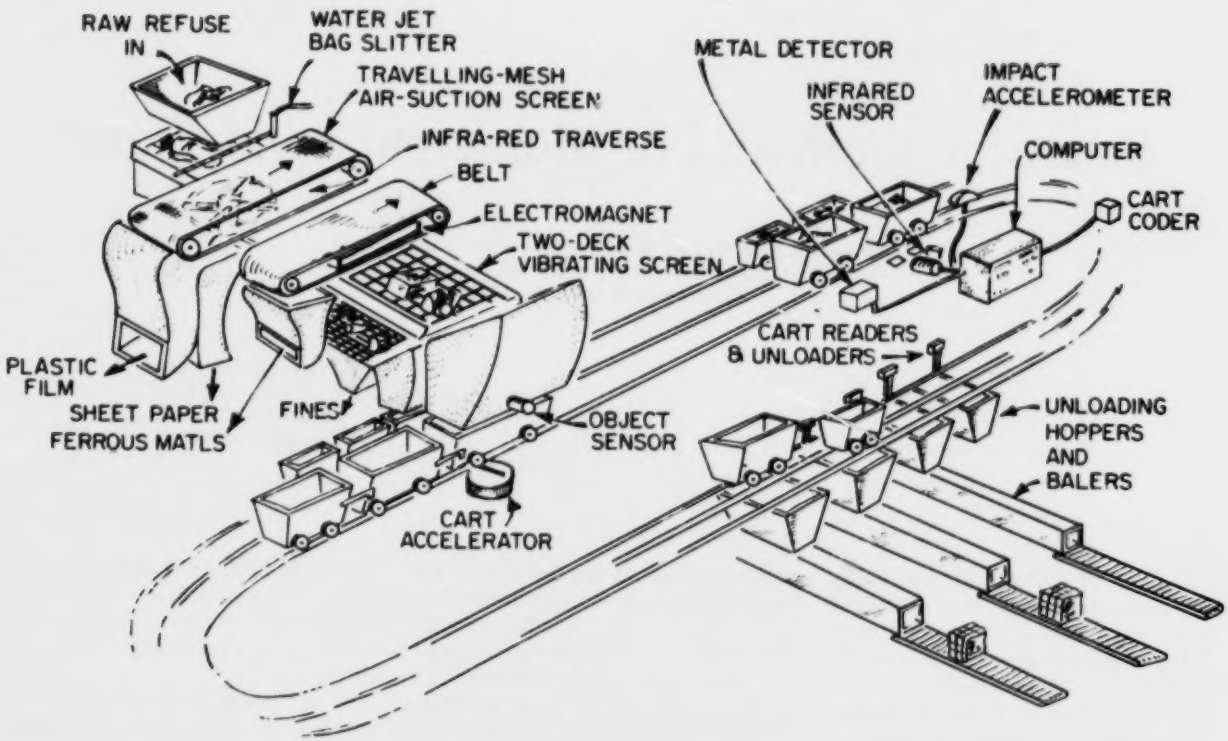

FIGURE 1 DIAGRAM OF PRESORTER AND LARGE-ITEM SORTER

end of the vibrating screen are positioned several carts, with guide funnels so that each piece of refuse has to fall into one or another cart. As a piece of refuse enters a cart, a sensor activates an accelerator, the cart is rapidly moved down its track and a new cart takes its place. Subsequently, carts are assembled in trains to pass smoothly over the sensors at a predetermined speed and a predetermined minimum spacing.

This large-item sorter is described more fully in a later section.

Report arrangement

This section concludes the introduction to this final report. The following chapter describes the collection of data which we used in the design of the plant. Subsequently, the design and performance analysis of the large-item sorter, the sensors, the computer control and sorting system, and the analysis and experimentation of the small-item sorter or vortex classifier are described. Some conclusions are made with regard to the design of full-scale plants using this approach.

The reproduction of all details of the work has not been attempted in this report. Readers are referred in appropriate places to earlier reports or to student theses for greater detail.

CHAPTER 2

PHYSICAL CHARACTERISTICS OF URBAN REFUSE

The material composition of refuse on a mass-percent basis has been frequently studied.[3,12] Investigations at M.I.T. and at Middlebury College, Vermont (where Professor Frank Winkler has been working on a parallel program of sensor development and data analysis in collaboration with us), have gone beyond the study of mass composition to examine in detail the size and weight distribution of individual items found in municipal solid wastes.[13] We have sought to answer such questions as: how many items per ton of refuse have dimensions larger than six inches; what fraction of the total weight do such items represent; what is the size and weight distribution of glass objects found in refuse; etc. In addition, we have carried out a detailed investigation of the qualitative nature of the refuse, breaking down principal categories such as paper into numerous sub-categories. Furthermore, the rich variety of composite or contaminated items has been recorded and taken into account in our data. Our refuse data base can be used not only for obtaining the general size characteristics presented here, but also for more specialized applications, such as providing input to a computer model of a refuse-processing plant. This has been successfully carried out for the M.I.T. system.

Refuse from a variety of geographic and economic areas has been sampled. Since the project is based at M.I.T. in Cambridge, Massachusetts, samples were collected in this essentially urban community. Four samples totaling 1,152 pounds were collected from high-, middle-, and low-income neighborhoods of the city. Four samples totaling 915 pounds were also collected and analyzed in Middlebury, Vermont, a town of 6500 population.

DATA COLLECTION

In the course of the study approximately one ton of refuse was examined on an item-by-item basis. For each object, the following data were recorded: weight, dimensions (length, width, and height) and material composition, classified into one of some 50 categories. Since a great many objects found in refuse are composites of two or more rather disparate materials, it was deemed desirable to classify such items by secondary and tertiary material composition as well. A common (and relatively innocuous)example might be a clear-glass container (primary material) with steel lid (secondary) and

paper label (tertiary). Objects which could not be adequately described by the use of three such categories were classified as "miscellaneous".

It was also necessary to establish criteria for defining what is an "object". In order to be considered a single object, an item consisting of several major parts should hold together when lifted by any one of them. Parts which broke away were considered to be separate objects. A stiff container such as a jar or a cardboard box was inverted for one second, and the portion of the contents which fell out was considered to be a separate object(s). Newspapers consisting of several sections folded one within another were generally considered to be single objects. More generally stated, "objects" were those items which would be expected to remain intact after a reasonable amount of mechanical handling. In practice, this criterion was seldom found to be ambiguous.

A special problem is presented by the common use of large plastic and paper bags as containers for domestic solid waste. Since a sizable fraction of refuse is found in such bags, any item-by-item reclamation system will require a mechanical device for rupturing the bags and emptying the contents. One such device is a water-jet slicer and vibrating screen, as is planned for the M.I.T. system. For our survey, bags were simply ripped open by hand. Bags which could be ripped by grasping at two points and giving a good tug were considered mechanically breakable, and again there was little ambiguity in this criterion.

For collecting the data, a large bag full of refuse was opened and its contents emptied into a clean barrel. Objects were then selected from the barrel and weighed, measured, and categorized. Measurements of flexible objects in particular were somewhat arbitrary, but were taken with the object in an "as received" condition, without either crumpling or straightening the object. Individual objects were examined until no objects with dimensions larger than about one inch remained in the barrel. Any remaining items were termed a miscellaneous collection, and its total weight was recorded with no attempt at additional classification.

The data were voice-tape-recorded by students working singly or in pairs. Subsequently the data for each object were punched onto cards for rapid analysis by computer.

Solid waste for examination was obtained in a variety of ways. The first sample of Cambridge municipal refuse consisted of about three tons delivered to the M.I.T. examination area by one of the city packer trucks. Two students working according to the procedures outlined above could examine some three to four items per minute,

and it soon became apparent that the volume of refuse on hand was somewhat excessive. After two weeks, over 600 pounds had been analyzed, and further examination was deemed to be inadvisable.

In order to check the variability of Cambridge refuse, three additional smaller samples were obtained. For these samples, refuse was collected from curbside in the early morning, before the municipal collection trucks arrived. Approximately 175 pounds of solid waste were collected from each of three neighborhoods, in high-, middle-, and low-income residential areas of Cambridge. Both loose and bagged refuse from a large number of households in each neighborhood was obtained, in an effort to make each sample as representative as practicable. Each of these samples was then removed to the M.I.T. laboratory for subsequent examinations by the same procedure outlined above. All four Cambridge samples were obtained in January 1973.

No statistically significant differences were found among the four Cambridge samples, although larger samples from various neighborhoods would undoubtedly reveal differences which might be the subject of an interesting sociological study. Since our interest is in obtaining figures applicable to typical municipal solid waste from all sources and neighborhoods, data from the four samples were combined to give a total data base of 1171 pounds of Cambridge refuse.

Four samples of solid waste were obtained in Middlebury, Vermont, over a period from mid-March to early June 1973. Middlebury has no municipal collection of refuse, but the private collector who services most of the local households was very cooperative in delivering a load of refuse to the laboratory for examination. Some 13 cubic yards from a packer truck were received, but since it was feasible to examine only a small fraction of this volume piece-by-piece, most of the refuse was removed forthwith.

Three smaller samples were subsequently collected at the town landfill. One of these samples consisted of refuse brought to the landfill by individuals, one was collected from the contents of a packer truck as it dumped, and one was a mixture simply collected from one side of the day's pile. The samples were chosen to be as representative as possible, and contained primarily domestic with some commercial refuse. Probably the most satisfactory method of obtaining a typical sample of manageable volume is to take material from the pile dumped by a packer truck. By choosing material from the lengthwise side of the pile, rather than from one end, a sample of the entire load may be obtained.

Each of the Middlebury samples was also analyzed by the same procedures outlined above. Data from these four samples were combined to give a data base of 915 pounds of Middlebury refuse.

BULK COMPOSITION

The composition of the Cambridge and Middlebury samples is shown broken down into nine principal categories on a weight (mass)-percent basis in table 1. Some fifty more-detailed categories into which the data were originally classified have been consolidated here for simplicity. For example, the "paper" category includes as sub-categories clean newsprint, contaminated newsprint, corrugated board, cardboard (e.g. food packages, etc.) kraft bags and wrapping paper, coated magazine stock, plastic-coated paper (milk cartons), writing or tablet paper, books, and "mixed dirty paper".* No "standard" set of categories for refuse constituents has as yet been adopted, but the list in table 1 is similar to those used in other recent surveys of solid-waste composition. Data from many sources on bulk composition of refuse have been compiled in recent studies by the National Center for Resource Recovery [12] and Battelle Memorial Institute.[3] The weights given in table 1 are on a "wet basis", i.e. the weights of objects are measured as received, without drying.

The percentages listed in table 1 show relatively large entries for "miscellaneous and uncategorized" materials. These reflect the fact that bulk composition analysis was tangential, rather than central, to the goal of this survey. As noted in the preceding section, only items with at least one dimension larger than one inch were handled and categorized. Smaller items were not categorized, and these constitute the bulk of the 15 to 20 percent miscellaneous material. In addition, such inorganic materials as brick and stone were placed in the miscellaneous category.

Comparison of the results in table 1 with those from other surveys indicates basic consistency with a few interesting differences. Both Cambridge and Middlebury have a significantly higher percentage of glass (primarily bottles) than the 10.3% or 9.0% of the NCRR or Battelle surveys, respectively. The low percentages of food wastes in the present samples probably reflect a number of factors: Cambridge has a separate municipal collection for food waste-- "garbage"-- and most of such waste

*Detailed categorization is very valuable in computer simulation studies.

TABLE 1

Bulk Composition (weight percent) of Refuse Samples.

	PERCENT BY WEIGHT (WET BASIS)	
	Cambridge, Mass.	Middlebury, Vt.
Paper	35.8	48.9
newsprint	(7.8)	(3.0)
Metals	9.2	9.1
ferrous	(8.3)	(8.8)
nonferrous	(0.9)	(0.3)
Glass	18.6	16.6
Plastics	4.1	2.4
Cloth, Rubber, Leather	5.2	2.5
Wood	1.1	0.4
Food Waste	5.9	4.7
Yard and Garden	0.5	0.3
Misc. and Uncategorized	19.6	15.1
	100.0	100.0

would be expected there rather than in the refuse collection sampled by us; Middlebury samples included a fair fraction of commercial refuse, thus tending to dilute domestic food wastes; and much of the uncategorized small material consists of food wastes. Low percentages of yard and garden wastes are to be expected because most of the samples were taken during the winter, and because Middlebury has an alternative yard-waste dump that is much more convenient than the rather distant landfill for most citizens.

Another interesting statistic is that newsprint made up only 8% of the Cambridge sample and 3% of the Middlebury one, compared to 12% estimated by Battelle. Both communities have active newspaper recycling programs which handle a significant fraction of the newsprint that might otherwise find its way into the refuse stream. In addition, the low Middlebury figure undoubtedly reflects the much smaller bulk and lower publication frequency of rural in comparison to urban newspapers.

SIZE TABULATIONS

Of greatest interest to us in carrying out the present survey was the size distribution of objects in refuse. Our findings are summarized in figures 2-7. Figure 2 shows the cumulative number of objects per ton of raw refuse whose longest dimension is greater than a particular length, plotted as a function of that length. The cumulative total weight of these objects is plotted as a function of length in figure 3. These figures show, for example, that a mechanical system for handling Cambridge refuse, working only with objects of length greater than five inches, would have to handle about 9000 objects per ton of refuse, and that these objects would represent some 70% of the total weight, or 1400 lbm per ton. For a system working with Middlebury refuse the picture is comparable, though somewhat more favorable, since only 5000 objects per ton have a length of over five inches, yet these account for 80% of the total weight. It should be noted that since a great many refuse objects are not rigid, the dimensions may be somewhat elusive to define. Flexible or collapsible objects were simply dropped on the measuring table as found and measured, since this probably approximates a general mechanical-handling system better than any other measurement scheme. As the figures show, independent samples from the two communities yield comparable results, but there are important local differences. Most notable is the much greater number of objects of dimension,two feet or larger found in Middlebury. Most of these were corrugated cartons from commercial establishments.

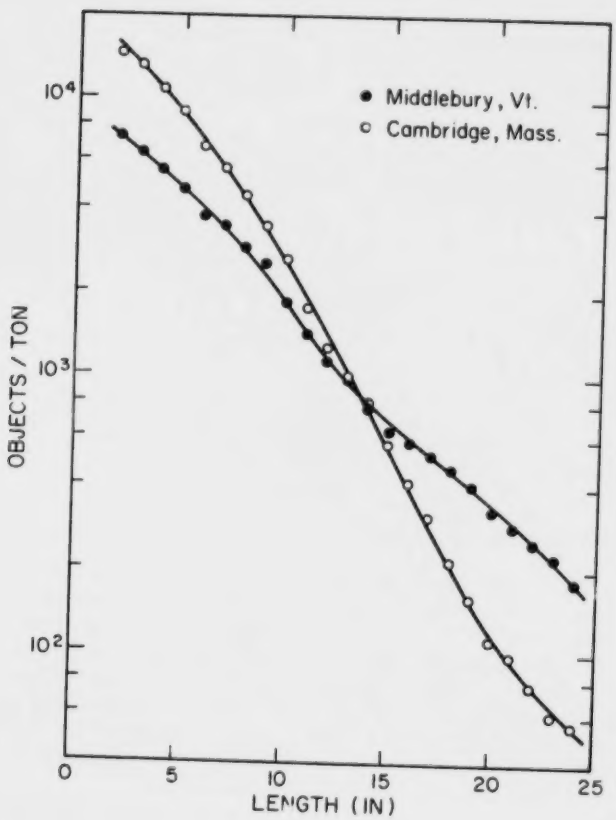

FIGURE 2 NUMBER OF OBJECTS PER TON OF RAW REFUSE HAVING LONGEST DIMENSION GREATER THAN GIVEN LENGTH.

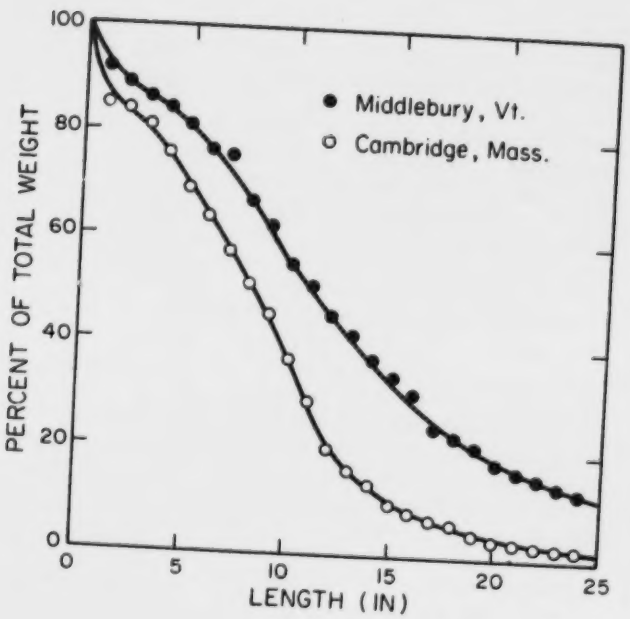

FIGURE 3 MASS-PERCENT OF OBJECTS WITH LONGEST DIMENSION GREATER THAN GIVEN LENGTH.

Figures 4 and 5 are similar to the preceding pair, but here the number and weight of objects which will pass through a wire mesh of various sizes are shown. For example, we see that about 3000 pieces per ton of Cambridge refuse, representing 50% of the total weight, would be sieved out by a vibrating screen of mesh five-inches square. These figures are based on the criterion that in order to pass through a given mesh an object must have at least two dimensions smaller than the mesh size. This amounts to a 100% screening efficiency, and actual vibrating screens might pass somewhat fewer objects. On the other hand, some flexible objects such as textiles might in fact pass through a smaller mesh than indicated by our measurements. Our results are intended to give reasonable estimates of what might be expected with various screens, and we hope to check them with our actual mechanical system in the near future.

Figures 6 and 7 show the number of objects per ton and weights tabulated as a function of length for some principal refuse constituents. Here the numbers and weights are not cumulative; instead, the height of each column represents the number or weight of objects, per ton of raw refuse, in each one-inch interval of length from two to 20 inches. The ">20" block at the right of each histogram represents the number or weight of objects greater than 20 inches in length. The area of each such block represents the same number of pieces or weight as an equal area on the accompanying histogram.

Cambridge and Middlebury data are combined here for improved statistics. The total height of each histogram column, as read on the corresponding vertical scale, represents the number or weight of objects per ton found in the combined sample. Cambridge and Middlebury contributions to these totals are shaded differently. Of the 2086 pounds in the combined sample, 1171 pounds are from Cambridge and 915 pounds are from Middlebury, or the Cambridge data account for somewhat more than half of the total.

As is apparent from the histograms, different materials have very different size distributions, and some interesting patterns emerge. Almost half of the total weight of metallics consists of objects between three and five inches in length (mostly cans, of course).* Furthermore, metallic objects make up 40% of the total weight of refuse in the three-to-five inch size range, as opposed to only 9% for refuse of all sizes.

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*The curious peak at 16-17 inches in the metals histogram of figure 7 is in a way spurious, since it results from a single object (a well-mauled baby carriage). This peak can be mentally spread out over the 10-20 inch range, since a much larger sample would undoubtedly contain many heavy objects of large size, with no particular concentration in any narrow range.

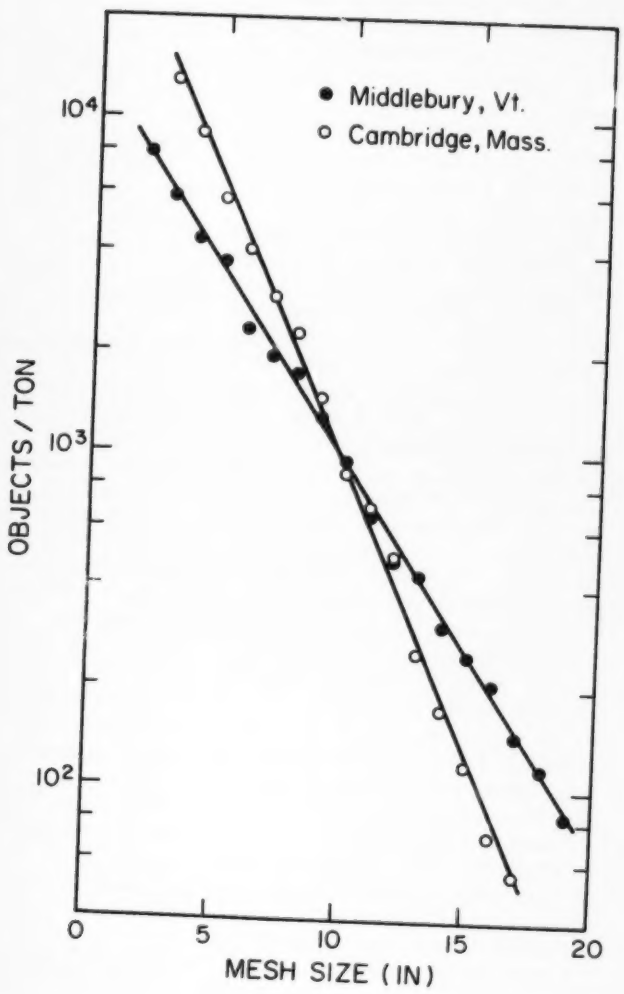


FIGURE 4 NUMBER OF OBJECTS PER TON OF RAW REFUSE WHICH WILL PASS THROUGH A SQUARE MESH

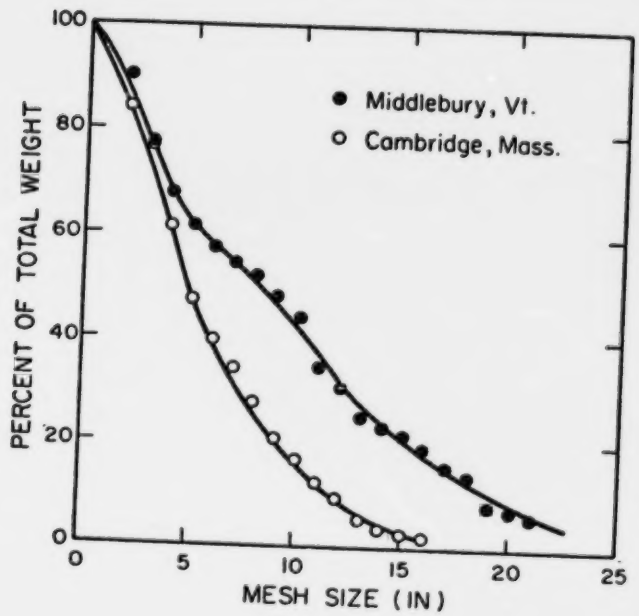
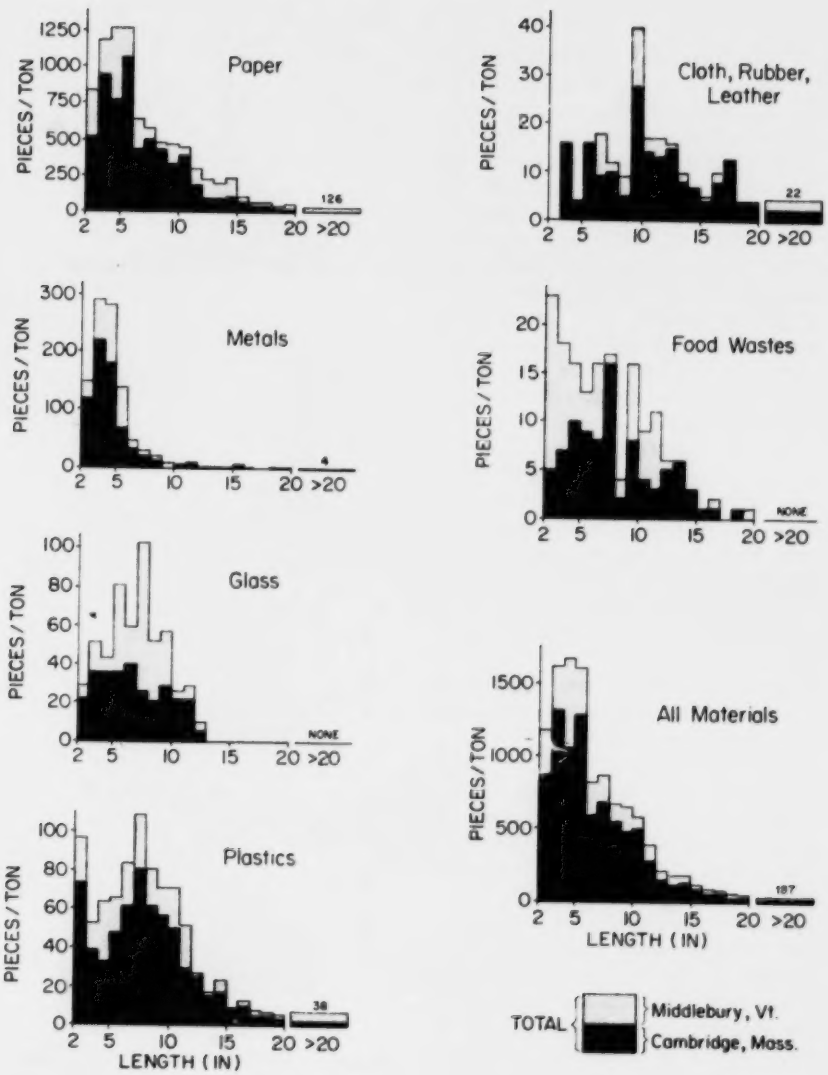


FIGURE 5 MASS-PERCENT OF OBJECTS WHICH WILL PASS THROUGH A SQUARE MESH



Total height of each bar gives weighted average of Cambridge and Middlebury data, with relative contributions indicated by shading. Note different vertical scales.

FIGURE 6 NUMBER OF OBJECTS PER TON OF RAW REFUSE VERSUS LONGEST DIMENSION FOR PRINCIPAL CATEGORIES

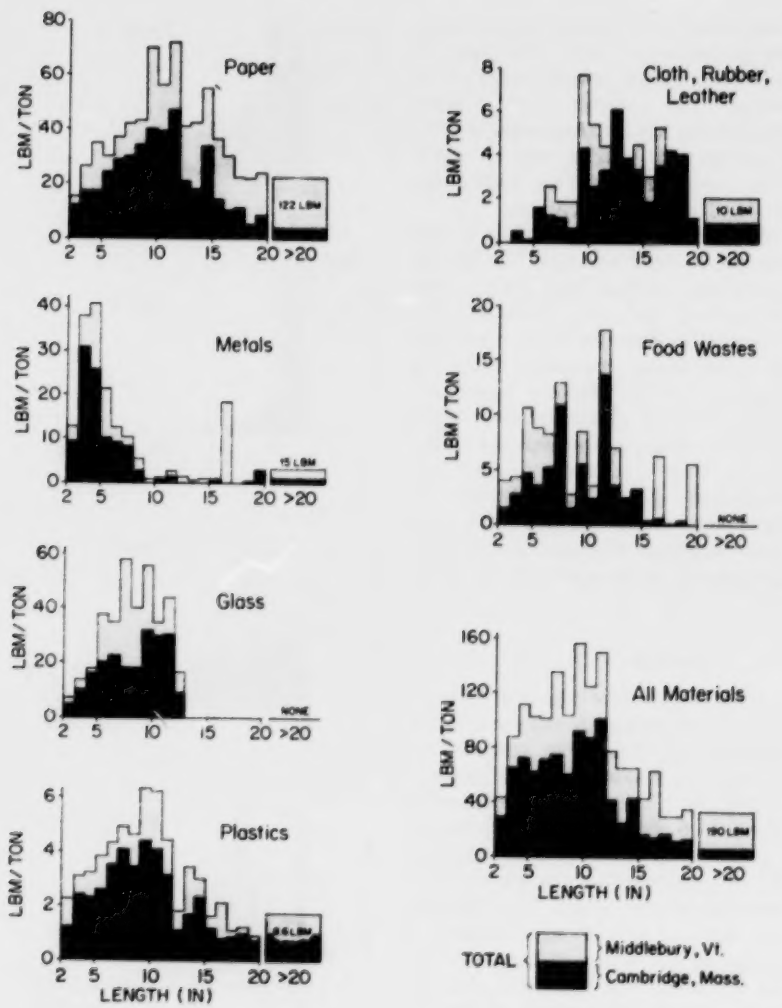


FIGURE 7 TOTAL MASS PER TON OF RAW REFUSE OF OBJECTS IN GIVEN LENGTH RANGES FOR PRINCIPAL CATEGORIES OF REFUSE.

Similarly, there is a "bottle peak" in the glass category between five and ten inches, and glass objects account for 38% by weight of the refuse in this range. Very few glass bottles are broken in the collection and dumping process. A separate but related study examined Cambridge refuse which had been discharged from packer trucks onto the concrete floor of a processing station. Some 94% of the bottles had remained intact through the rather grueling process of discard, collection, packing and dumping.

The objects greater than twelve inches in length are predominantly paper products, 67% by weight. Of all the paper products, just over 50% by weight fall into the over-twelve-inch range, yet the number of objects here is rather small, only about 1000 pieces per ton of refuse. Furthermore, the overwhelming majority of paper products with high recycle value, such as bundles of newsprint and corrugated cartons, falls into this size range.

Clearly sorting by size can be an important process in any system for automated recovery and recycling of solid waste. Size sorting alone cannot, of course, give a pure product of glass, newsprint, etc., but as the figures above indicate, sorting by size may be able to "enrich the ore" from which such products are to be eventually recovered.

CHAPTER 3
DEVELOPMENT AND DESIGN OF THE LARGE-ITEM SORTER

The selection of large items from a mixed mass of municipal wastes, to determine their composition, and to place them in one of a number of alternative streams, presents a considerable challenge. It is the process which has been carried out in manual sorting for many years. To reproduce the exact human procedure seemed inappropriate. However, we were approached by a local company which had partly developed a process for recognizing shapes, and which believed that it could develop this procedure to the point where bottles, magazines, and other definitely recognizable constituents of solid wastes could be removed from a mixed mass. We did not have the funds to transfer to this development, but we recognize that it might have promise.

The M.I.T. approach consisted essentially of first singling out large items and then taking readings from a succession of sensors until the identity of the material or materials in each item could be determined with reasonable certainty.

The most difficult part of this process turns out to be the singling out: the separation of clumps of material into separate objects. A human being knows that he is looking at one item: a sensor receiving a varying signal for a short period of time will not know if it is looking at two items in close proximity or one heterogeneous item. A person would either know immediately or would pick up part of the item to see if it came up as one piece or more. We used this procedure for taking data (see chapter 2) and we considered singling out items by means of a series of suction heads. We rejected this idea because we thought there might be too many items with surfaces too irregular or too porous to be picked up easily by suction.

We therefore chose the alternative route of spreading out the refuse to such an extent that there is a high probability of there being a space surrounding each item. We also mechanically agitated the refuse mass to break up clumps. Both these functions were performed to a large extent on a two-deck vibrating screen. The input feed was divided among five or six streams at this vibrating screen, the whole assembly being termed a "presorter". Loose paper and plastic film were to be removed by an overhead fan and a transverse open-mesh belt (see chapter 6 for description of film-removal experiments). An overhead magnet and transverse moving belt were planned to remove the ferrous metals (neither the film nor the ferrous-metals extractors were fitted to the pilot process).

Fines passed through the vibrating screen and larger items in two sizes were retained on the upper and lower decks.

The vibrating screen could be inclined at various angles to produce a faster or a slower throughflow. Greater inclination obviously gave a greater throughflow and increased separation between items, but screening efficiency per unit length was reduced at above some critical rate or angle. An improvement in screening efficiency was obtained by changing the normal simple harmonic motion of the screen to a more complex motion with high end-of-travel accelerations. Screening tests are reported by Malarkey.[14]

A further tendency to single out individual items was obtained by allowing the refuse to fall for a short distance down a chute fitted to the end of the vibrating screen. At the end of the chute was the leading cart of a queue of similar carts. (In a full-scale plant, there would be several carts positioned below the end of the screen, each cart being the leading one in a queue on a separate loop track). When a large item fell into a cart, it broke a light beam which triggered an electromagnetic clutch, accelerating the leading cart and replacing it with another. The acceleration was accomplished by a rotating arm, carrying pins at the extremities, engaging in transverse channels on the underside of each cart. By impulsively moving this arm, by means of the electromagnetic clutch, through 180 degrees, the carts underwent simple harmonic motion during acceleration and deceleration.

As initially constructed, the accelerator could dispatch six carts per second. This provided another capability for clumps of refuse to be broken up. The delay period before the acceleration commenced could be adjusted so that a complete bottle, for instance, would be within the cart before it was accelerated. Should there be something adhering to the bottle, there would be a good chance of the two pieces becoming separated during the acceleration. The second item could then fall into the second cart. If the two pieces remained together in one cart, the different readings given by the sensors would lead to the contents of the cart being either recirculated to the input feed or sent to the hammermill.

DESIGN SPECIFICATIONS

A challenge encountered in the design of a sorter of this type was the randomness of the input feed. We characterized this randomness by specifying that the cart system must be

capable of handling a maximum of five objects per lane in any one second and ten objects per lane in any four seconds. This performance specification was the result of a guess as to the performance of the presorter on raw refuse. It would probably need modifications in the light of experience. Choosing the specifications enabled other design choices to be made in the handling system, such as the maximum necessary number of carts in the accelerator-input queue, and the speed and cart density of the conveyor which moved the carts around the track after the initial acceleration period.

CART CONVEYOR

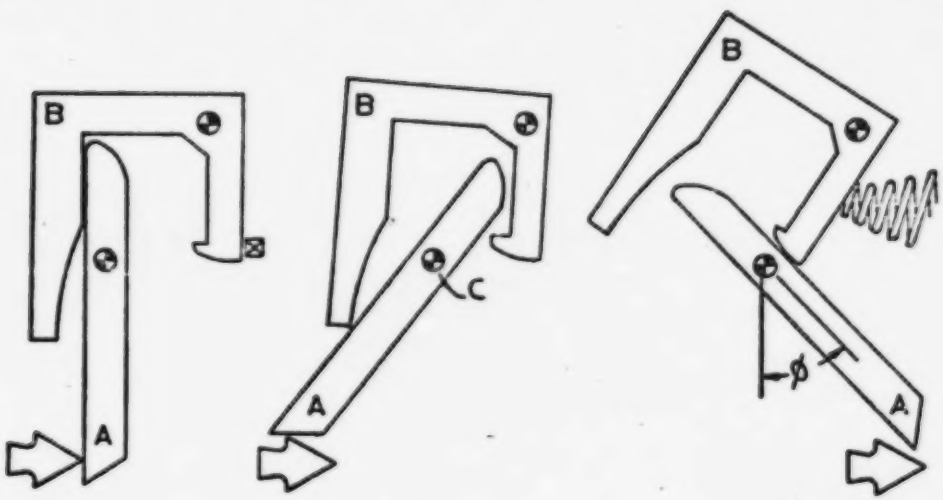
A chain conveyor carrying spaced drive pins was used to move carts steadily around the track past the sensors and past the unloading stations.[14] The drive pins engaged a cam on the side of the carts (figure 8). The cam was automatically released whenever a cart bumped the rear of a stationary cart in the accelerator queue. At the same time a latch attached the two carts together (figure 9).

REFUSE-SENSOR INTERACTION

As can be seen in the cross section in figure 10, the bottom of each cart incorporated slits aligned along the direction of travel. The sides of the cart bottoms were sloped so that all refuse in the category of large items would roll or slide to the point where at least some part of the item was over some part of the slit.

The proximity or contact sensors, which in the prototype were the metal detector and the impact sensor, were fitted in shaped housings which protruded through the slits of passing carts and which forced items of refuse in the carts to ride over the housings (figure 11). The infrared sensor, and later sensors such as color comparators, merely focus through the slit onto the rectangular area in which refuse should be found.

This system worked well in the prototype with the large items selected for the refuse sample. In practice, we would expect to have to take additional measures to deal with long, thin items such as hammer handles which, although small enough to pass through the vibrating screen, might in fact



a) driving c) over-riding b) releasing

FIGURE 8 DRIVE PINS FOR CART SYSTEM

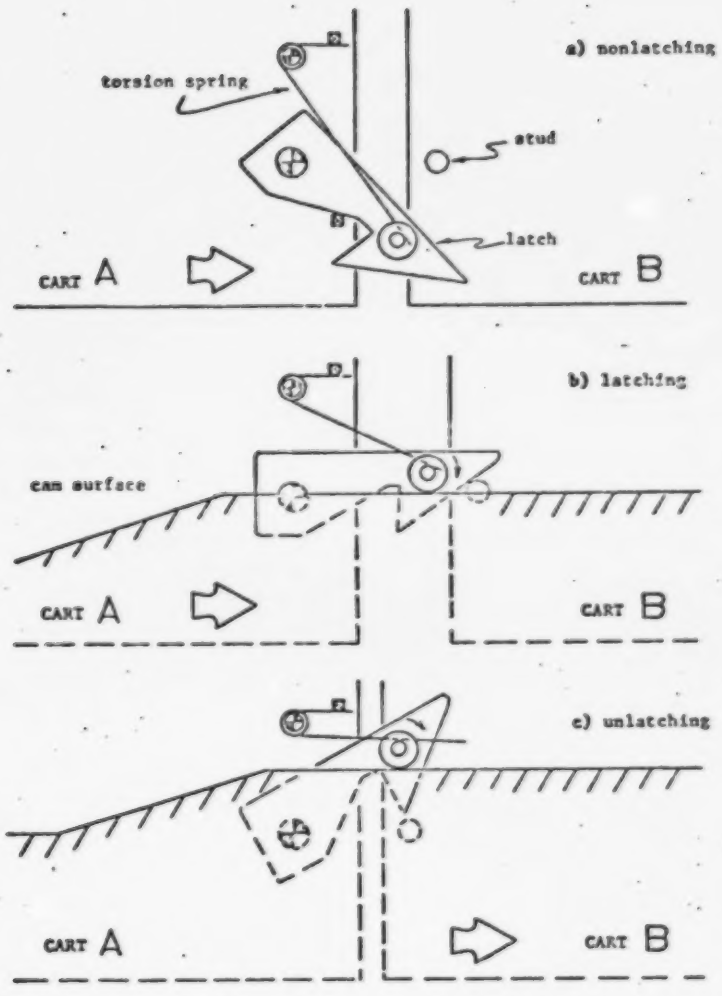


FIGURE 9 CART COUPLERS

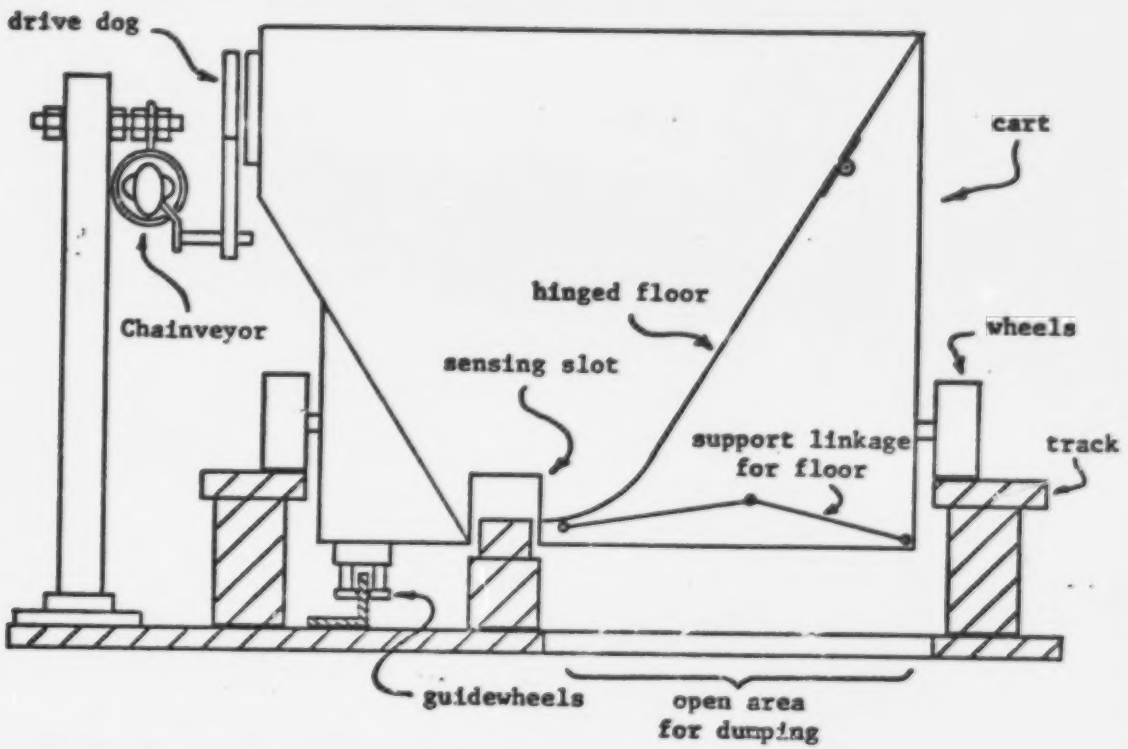


FIGURE 10 CROSS SECTION CART

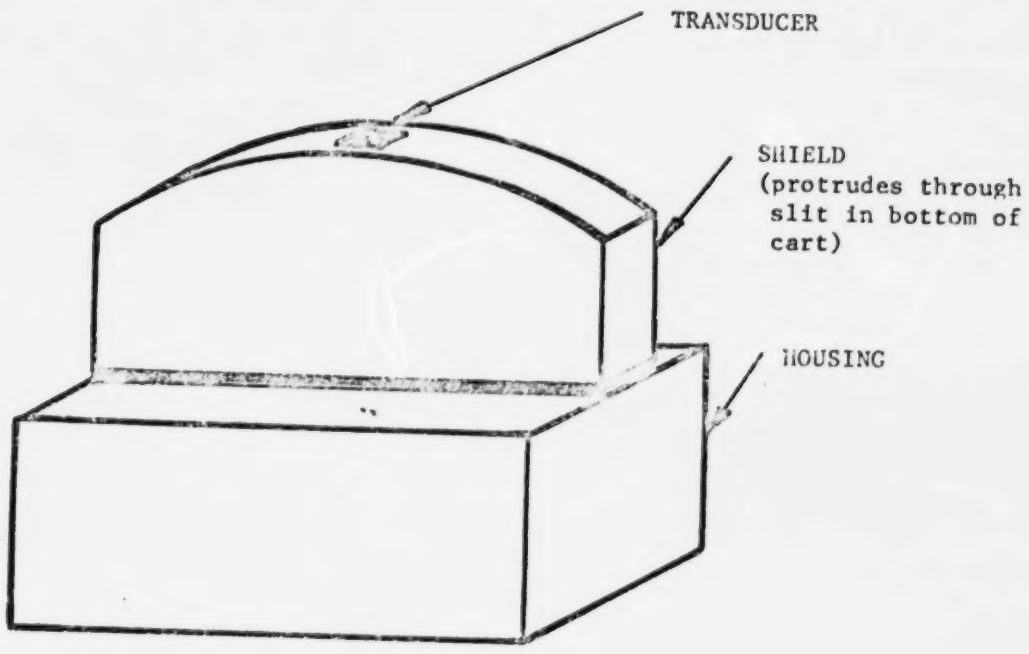


FIGURE 11 HOUSING FOR METAL DETECTOR AND IMPACT SENSOR

slide over it and eventually pass perhaps partly through the slit in a cart. Possible steps which would be taken are to agitate one section or all of the vibrating screen in such a manner as to rotate long, thin items and thereby to allow them to pass through the screen.[14] A second, and necessarily additional, approach is to have a detector ahead of the principal sensors to activate the unloading sequences for a cart from which an object is found to protrude. Problems are also expected with large textiles such as rugs and bedsprings, and loose pieces of wire, string, or rope. These components cause problems in all refuse-handling facilities, and at present there seems no alternative to the employment of human review either in person or through closed-circuit T.V., as used, for instance, at Lone-Star Organics in Houston.[15]

UNLOADING ARRANGEMENTS

The processing by computer of readings from the sensors, the subsequent coding of each cart, and the reading system are described in chapter 4. The results of these operations were that the cart passed along a series of reading stations, each of which had the capability of closing a circuit which would start the unloading process. The circuit was closed only when the code on the cart corresponded to the code which had been previously assigned to the reading station.

When the circuit was closed, a solenoid deflected a pivoted tubular cam under the track. A roller-bearing follower at the bottom of the approaching cart then engaged the cam and the bottom of the cart would be quickly opened by a toggle action. (figure 12). The cart would be still moving, and when sufficient distance had elapsed for any refuse items within the cart to have fallen into the hopper below, a second linear cam reclosed the cart bottom.

This system worked well in the prototype. Problems are expected with light, sticky refuse, and it may be desirable or necessary to incorporate an air nozzle to be switched on when the cart is unloading to speed the process. Presumably this would be necessary only for paper, plastics, and textiles, and not for bottles and cans, for instance. At some time before the carts are recirculated to the accelerator queue it is expected that a steam or hot-water rinse of the carts' interiors will be required.

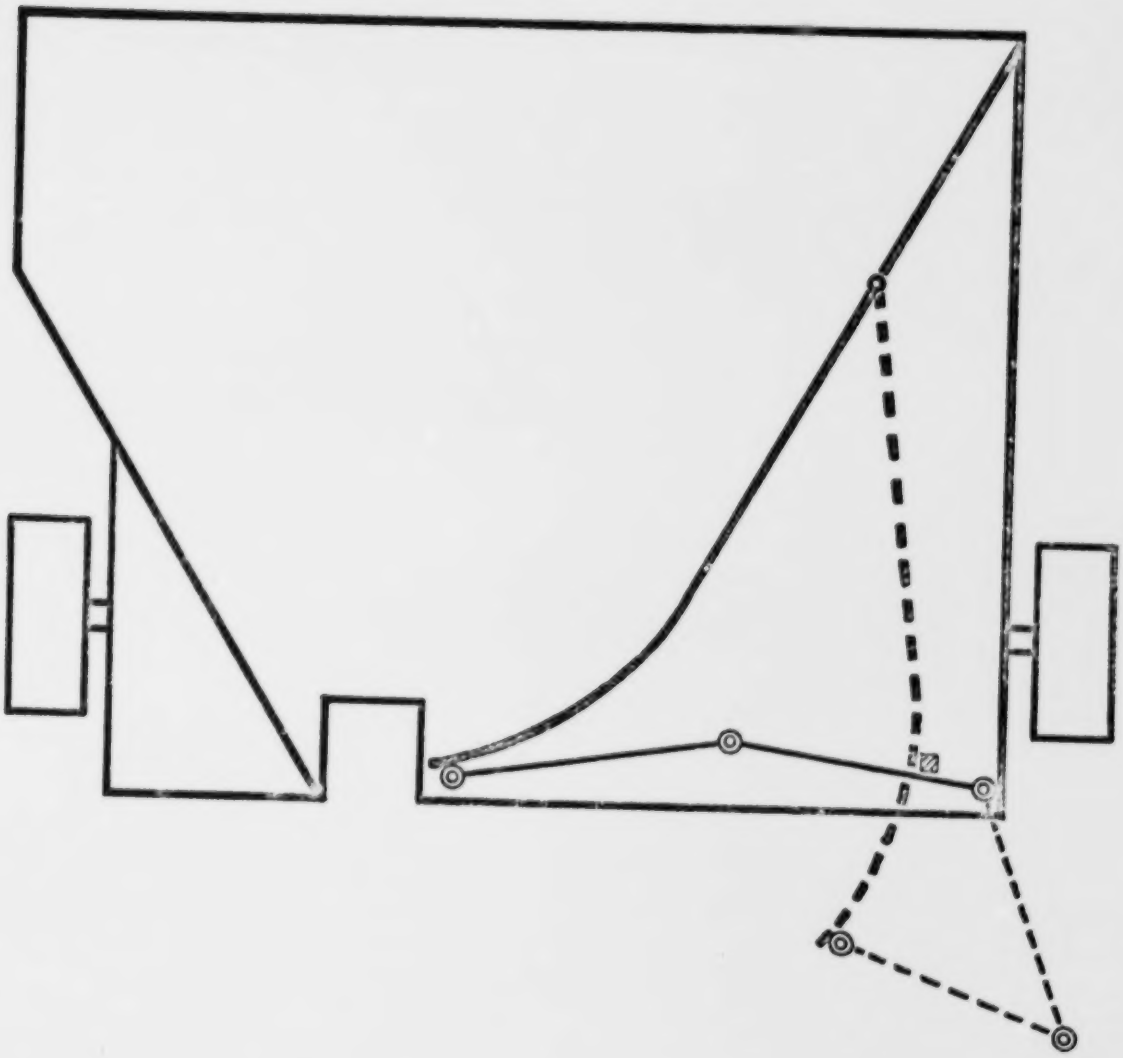


FIGURE 12 TOGGLE-ACTION LATCH FOR CART DOOR

DESIGN OF FULL-SIZE PLANTS

Certain modifications and refinements would be necessary for the incorporation of the presorter and large-item sorter concepts into the design of a full-size plant. In addition, while some components, such as the vibrating screens, would become larger, other components, such as the cart systems, would simply be duplicated. Some of the refinements have been mentioned above. The carts themselves would preferably be constructed of high-density polyethylene, glass-fibre-reinforced nylon, polyurethane, or other tough material having some resiliency. Relatively low mass is desirable in order to keep down stresses in the accelerator. The arrangement used in the prototype of accelerating just the leading cart in the entrance queue and relying on intercart latches to transmit the acceleration forces leads to unduly high stresses and loads. A modified system in which each cart in the queue is accelerated simultaneously but independently is probably preferable.

Maximum feed rate for carts

An acceleration capability of about five carts per second seems to be a good match with presently forseeable sensing rates and with the flow rate of vibrating screens. In addition, at, say, double this feed rate, impacts of refuse within the carts might break bottles and might cause the ejection of some other items.

The permissible maximum rate of operation of the accelerator would obviously depend to some extent on the size of the carts. For plants having capacities greater than 100 tons per day, more than one lane of carts would be necessary. There would obviously be a cost saving in having at least two different sizes of carts, each cart size being fed by one deck of a multi-deck screen.

Number of different sizes of carts and numbers of lanes required

Malarkey analyzed the advantages and disadvantages of having one, two, and three cart sizes.[14] and concluded that two cart sizes, ten inches and twenty-four inches wide, would be optimum. The number of cart lanes required for different

plant capacities is shown in figure 13. Some of the assumptions used in devising this design figure are that the maximum velocity of the carts would be five feet per second; that the cart length would be at least twice the mesh size of the screen feeding it; and that the plant would operate 16 hours per day.

Vibrating-screen size as a function of mass-flow

The size of two-deck vibrating screens as a function of plant capacity are shown in figure 14, as determined by Malarkey.[14]

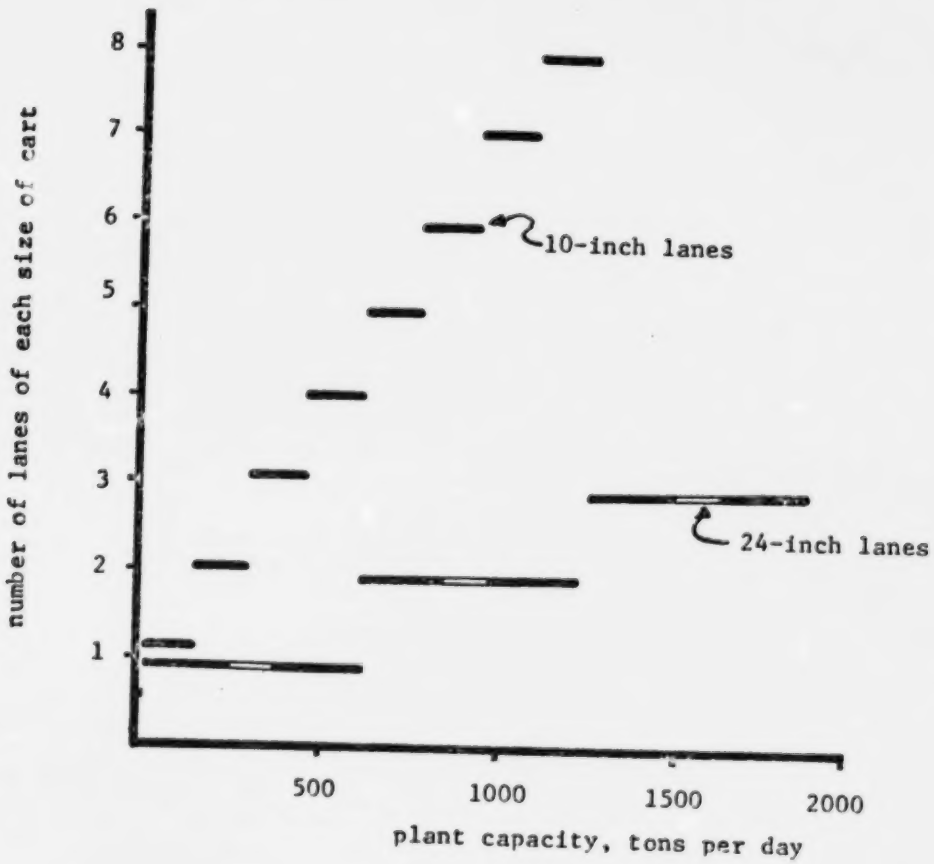


FIGURE 13 NUMBER OF CART LANES REQUIRED IN FULL-SIZE PLANT

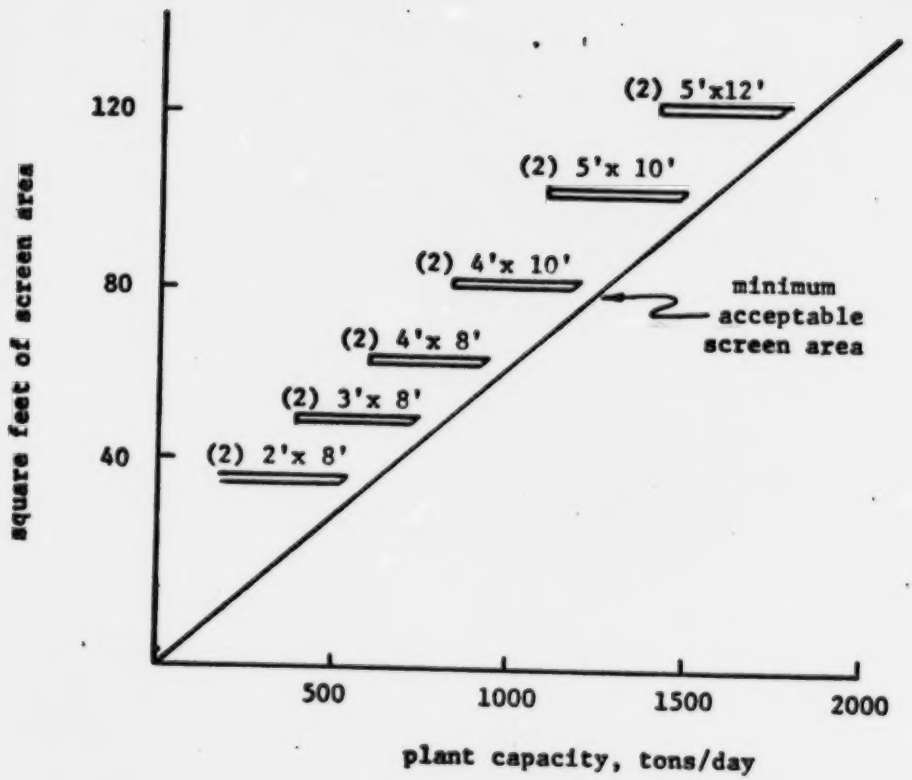


FIGURE 14 SIZES OF VIBRATING SCREENS NEEDED FOR FULL-SIZE PLANT

CHAPTER 4

DEVELOPMENT AND OPERATION OF THE INSTRUMENTATION SYSTEM

BACKGROUND

At the beginning of the present two-year grant period (June 1971), the status of the instrumentation system was as follows. A survey had been made by Smith,[11] Wilson, and Senturia [10] of all apparent methods which might be used to obtain enough data on refuse items to permit some form of automatic classification of these items. The survey covered the entire electromagnetic spectrum, from low-frequency radio waves (conductivity), to microwaves, infrared, visible, ultraviolet, and x-rays. The relative merits of the kinds of information which could be obtained in each spectral range were examined. In addition, acoustical methods were examined, including measurement of sound velocity, and the use of acoustic reflectometry with ultrasonic waves. The criteria used for selecting the methods for further development were as follows.

1) The sensor should be a multiple-output sensor, capable of providing a classification of a given piece of material into one of several categories.

2) If a sensor method was already available commercially, it should be employed. There were, in fact, no commercially available multiple-output sensors except for highly sophisticated research-style instruments capable of examining highly detailed spectroscopic records and comparing them with standard spectra. These research-style instruments were judged unsuitable for the relatively coarse sorting operation envisaged for this plant, and they required either careful sample preparation or an undue length of time to produce a reading or both.

3) The combination of sensors selected should have a reasonable liklihood of being able successfully to separate the principal recyclable refuse components, these being glass, paper, metals, and plastics.

4) The objects being sensed should not require special preparation - eg cleaning, etching, polishing, - and the readings should be capable of being made in air, rather than in a vacuum, so that "raw" refuse could be sorted.

5) Readings should be obtainable within a few milliseconds of exposure to the sensors, so that a small sorting plant could have a high throughput.

SENSOR SELECTION

The results of that survey and of several preliminary experiments were that two sensors were selected for development, the infrared sensor and the impact sensor.

Infrared sensor

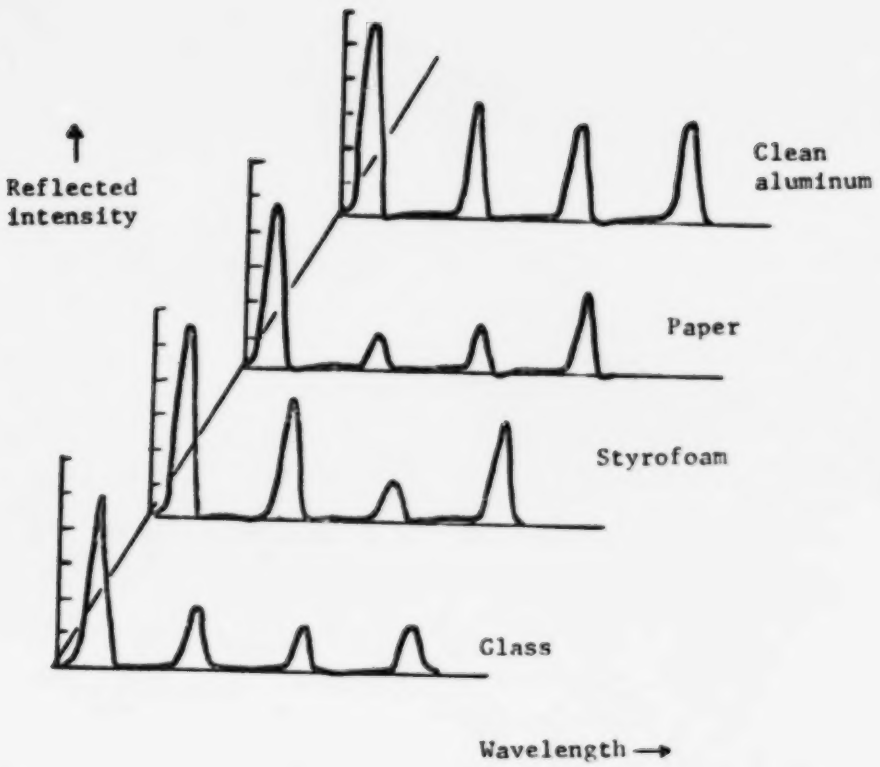
The infrared sensor [16] uses the principle that the spectrum of infrared light which has been diffusely reflected from a surface will show all of the major infrared-absorption lines characteristic of the reflector. By surveying the reflection spectra of many refuse items, a set of wavelengths was chosen which could indeed provide useful differentiations among classes of objects. A pattern-recognition algorithm using linear-separation techniques was developed which could successfully classify metals, glass, cellulose, and plastics on the basis of the relative intensities of the light reflected at the four infrared wavelengths (see figure 15).

Lewis [17] then built a prototype instrument which used a globar infrared source, a rotating filter wheel to select the four wavelengths, and a PbSe photodiode detector. The amplitudes of the photodiode signals corresponding to each wavelength were stored in analog track-and-hold memory circuits. This set of stored voltages constituted the "pattern" on which the pattern-recognition algorithm could work. The specific algorithm used has been published elsewhere. [18] A special-purpose analog computer was built to implement the algorithm in real time. The complete assembly was able to measure the infrared reflection spectrum and to calculate a classification.

The accuracy of this prototype version was not good, and the analog computer was cumbersome at best. These initial experiments, however, demonstrated the fundamental soundness of the method, and served as the basis for the subsequent work.

Impact sensor

The impact sensor uses an effect, discovered by Wilson and Smith,[19] that the time dependence of the acceleration of a hammer or impact tool striking a refuse item is characteristic of the kind of material being struck. An accelerometer is mounted on an impact tool which is allowed to strike the



The amplitudes of the four peaks constitute the pattern fed to the computer for classification

FIGURE 15 SAMPLE SPECTRA FROM THE INFRARED SENSOR

object under test. The shape of the impact waveform (figure 16) varies with the elastic and plastic properties of the material. Steel gives a sharp "ping" while wood gives a relatively dull "thud", just as one would expect on the basis of everyday experience. What might not be expected, however, is that the shapes of these impact waveforms can be quantitatively analyzed and used as a "pattern" for a pattern-recognition algorithm similar to that used for the infrared sensor. Hibberd [20] and Epstein [21] developed Wilson and Smith's idea into a working impact sensor which used an impact tool operating in free fall, track-and-hold memories to store parameters characteristic of the acceleration pulse, and a specially-built analog computer for implementation of the pattern-recognition algorithm. The details of the algorithm can be found in reference 18. The performance of this prototype circuit was quite good on samples with well-defined geometries, such as plates of glass, plastic and metal. The free-fall nature of the impact tool, however, made the impact velocity impossible to control when irregularly shaped objects were being struck. Nevertheless, the early sensor was able to correctly classify steel, aluminum, glass, and wood.

By the end of the first grant period (June 1971), these prototype sensors were working and enough familiarity had been gained with their operation to permit the development of a substantially more elaborate instrumentation system incorporating new versions of these sensors. The development of this instrumentation system was done during the second grant period (June 1971 - August 1973), and is summarized in the following section.

PROGRESS SUMMARY

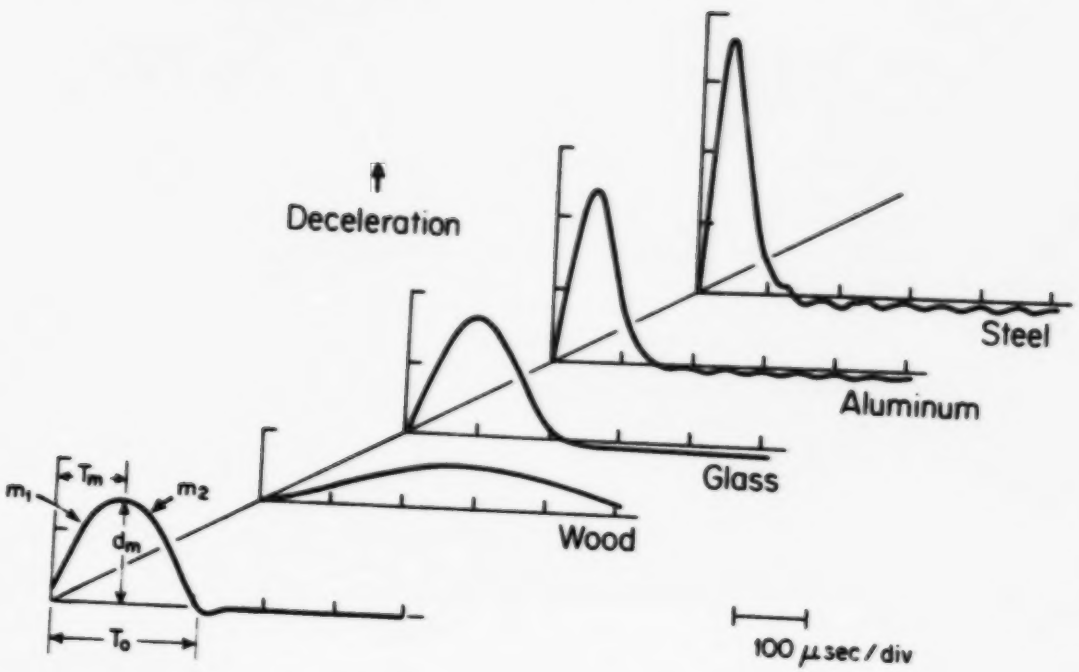
Progress on the instrumentation system during the present contract period consisted of:

1) the development of a digital-computer facility for on-line data acquisition, data processing, and plant control;

2) the development of a vibrating impact sensor;

3) significant improvements in the operating characteristics of the infrared sensor; and

4) the assembly of a prototype large-item sorter which included automatic cart-loading, the use of the infrared



Parameters such as ascending slope (m_1) peak height (d_m), and time-to-maximum acceleration (T_m) are measured electronically and fed to the computer for processing.

FIGURE 16 IMPACT-SENSOR DATA FROM TYPICAL SAMPLES

sensor and a metal detector to sense the objects in the cart, on-line classification by the computer, and cart-unloading at the correct unloading station.

At the conclusion of the grant period in August 1973, successful operation of this two-sensor prototype sorter was accomplished, with nearly perfect sorting of samples of metals, glass, plastics, and cellulose. A short film record of the operation was made to supplement the earlier documentary film made for EPA.

Succeeding sections of this chapter address each of the items outlined above. Descriptive summaries rather than exhaustive details are provided here; additional details on individual subjects can be obtained from student theses cited in the references.

Digital-computer facility

The acquisition of a digital-computer facility for data acquisition, data processing, and plant control was begun by Lingel and Senturia in the fall of 1971. A search was made of available minicomputers, and a comparison was made among leading brands using as a criterion the suitability for the particular calculations needed by the sorting plant. A secondary criterion was system economy. A decision to purchase a Computer Automation Alpha-16 minicomputer was made, and installation of the hardware began in December 1971.

The complete facility (total hardware cost - about $16,000) at present includes the following components (see figure 17):

1) an Alpha-16 minicomputer with 4K of core;

2) a Computer Operations dual Linctape magnetic tape unit;

3) an ASR-33 teletype;

4) a Digitronics high-speed paper-tape reader; and

5) a modified television set which has been adapted for simple text display.

The system now operates with all standard software on magnetic tape. Computer Automation's operating system for the Alpha-16, which includes editing, assembling, loading, and debugging routines, has been stored on tape and can be loaded into the computer with the use of an executive program developed by

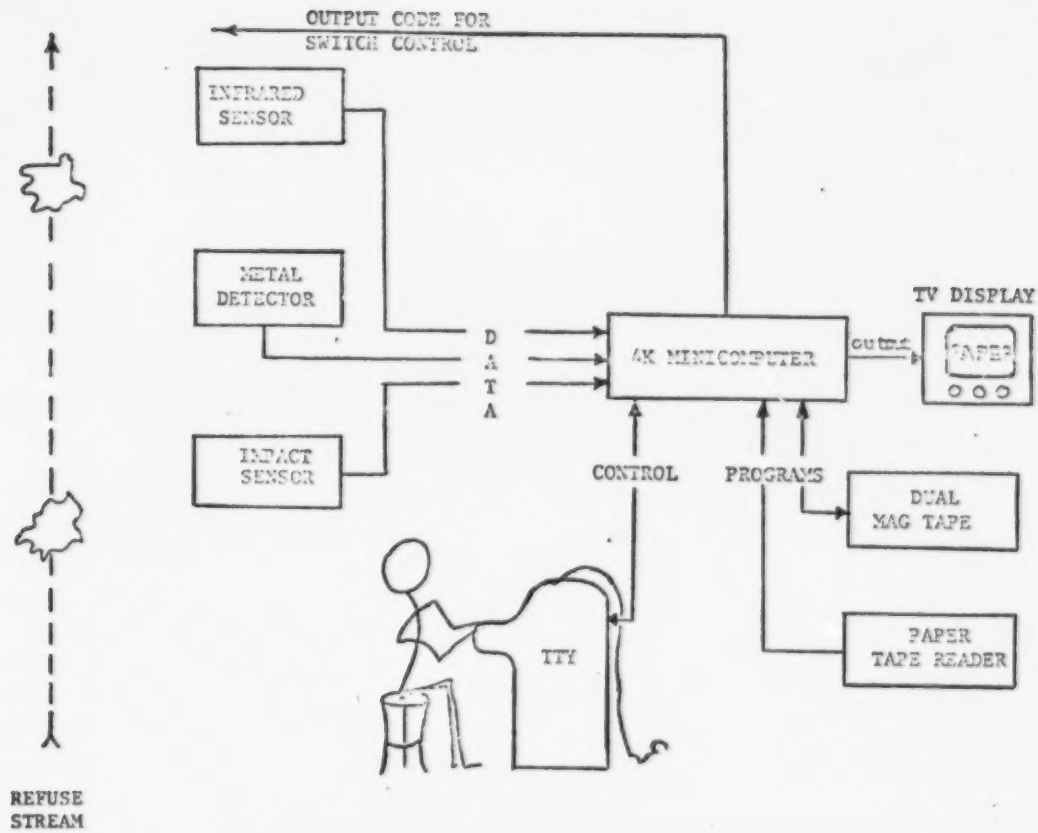


FIGURE 17 LARGE-ITEM SORTER INSTRUMENTATION SYSTEM

Lingel.[22] In addition, the Computer Operations' executive which controls Linctape reading and writing can also be loaded with the Lingel executive, permitting any program stored on magnetic tape to be loaded by typing two control words into the teletype. A limited version of BASIC is also available on our tape library, permitting the computer, when not committed to operations with the refuse system, to be used by non-experts for general calculations.

Remote data entry into the computer has been made possible by the development by Waal [23] of interface circuitry for a Memodyne digital cassette tape recorder. Her thesis reports the adaptation of a Memodyne write unit for portable field-encoding of data about refuse items, and the development of computer software for interpreting data patterns written on tape cassettes.

Vibrating impact sensor

It has already been stated that free-fall versions of the impact sensor were impossible to control when the object being struck had an irregular shape. Early experiments also showed that impact velocity had an effect on the shape of the impact waveforms. Therefore, shortly after the first demonstration of successful sorting with the free-fall impact sensor, Hibberd began the development of a vibrating impact sensor [24], a development which has been carried on subsequently by Kurtze.[25]

The idea behind the vibrating impact sensor is that one would like to control the velocity of the impact tool, and one would also like to make more than one impact with each sample. Figure 18 shows what the ideal motion for such a vibrating sensor would be. The impact tool is displaced at constant rate until it reaches a preset maximum, at which point the tool is rapidly reset to zero displacement for the start of another cycle. In this ideal picture, the impact tool is accelerated only at the turnaround points. Figure 19 shows schematically how the sensor would respond to an impact. In the present embodiment of this concept, the resetting to zero occurs a fixed delay time after the impact waveform has reached zero following impact. Gating circuits are used to prevent the acceleration signals due to impact from getting confused with the acceleration signals produced by resetting.

Hibberd built the first version of the vibrating impact sensor by mounting the accelerometer to the cone of a loudspeaker,

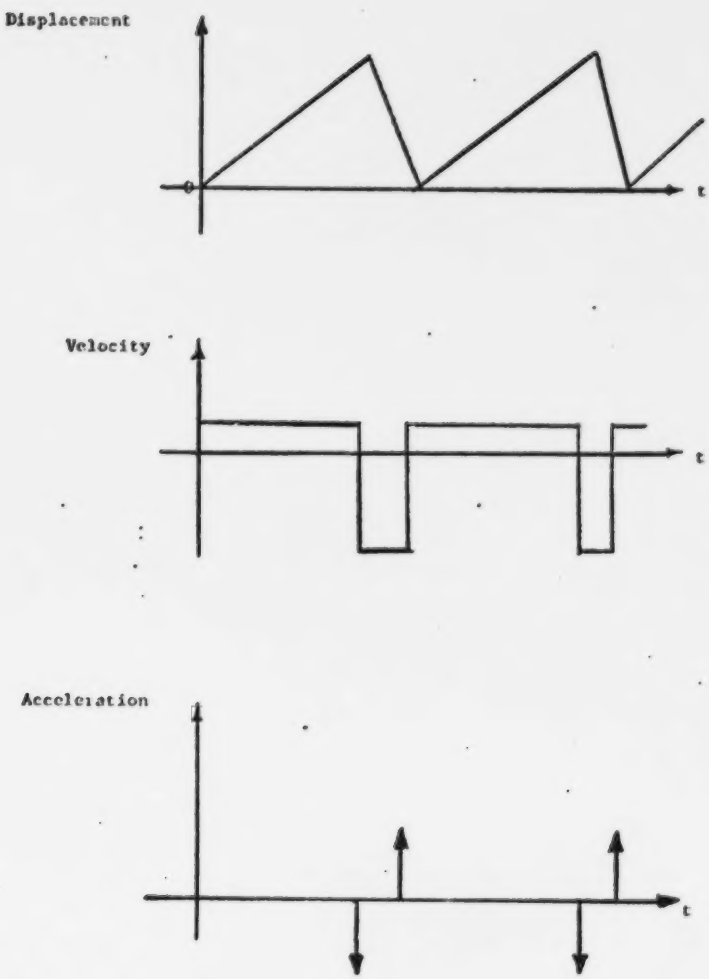


FIGURE 18 IDEAL MOTION FOR A VIBRATING IMPACT SENSOR WITH NO IMPACT

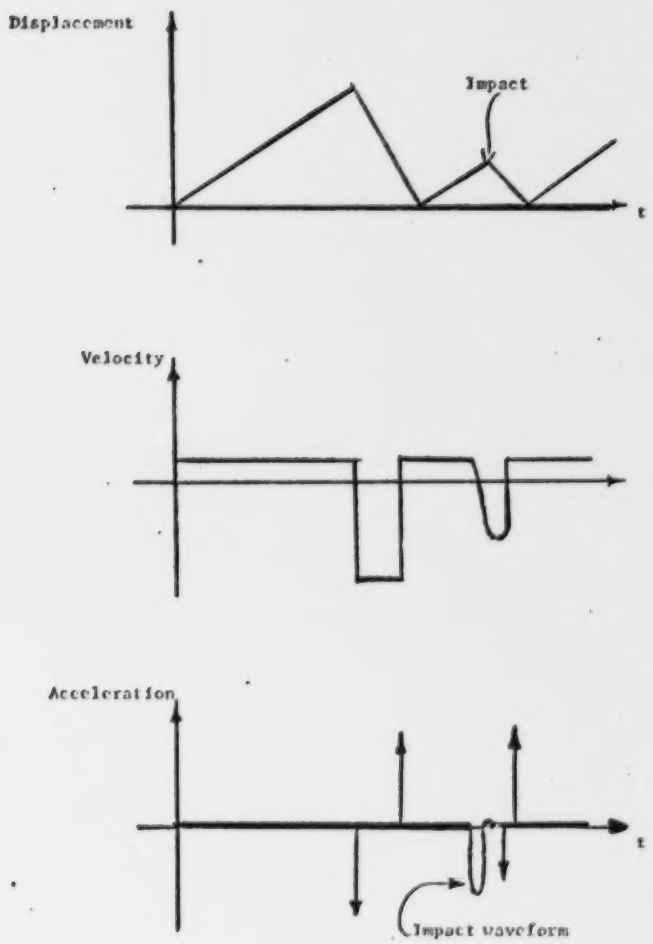


FIGURE 19 IDEAL MOTION FOR A VIBRATING IMPACT SENSOR WITH IMPACT

and then driving the loudspeaker with a current waveform which yielded the correct motion. Several problems were encountered in Hibberd's design. First, the inertia of the speaker had to be compensated by suitable adjustment of the speaker-drive waveform. Since Hibberd's design included no overall system feedback to control the speaker motion, this compensation adjustment had to be made using an externally generated waveform. As a result, perfect compensation could not be achieved, so that actual acceleration waveforms showed ringing following the turnaround acceleration spikes. This ringing, although small, was sufficient to interfere with the impact waveform.

Kurtze has modified Hibberd's design for closed-loop operation, in which the accelerometer signal is used to derive velocity and displacement waveforms. An overall control signal is then applied to the loudspeaker with the compensation signal being derived from a proper combination of acceleration, velocity, and displacement waveforms. By proper choice of control function, Kurtze has been able to stabilize the accelerometer motion to get good impact signals. Kurtze has also completed the construction and debugging of a computer interface originally designed by Lingel, which accepts the impact waveform and reads from that waveform the peak acceleration, the time to peak acceleration, the maximum leading-edge slope, the maximum trailing-edge slope, and the time required for the waveform to fall to 10% of its peak. These five parameters constitute the pattern. The interface circuit successively converts each parameter to digital form, and reads the numbers into the computer. Final testing of this system is now in progress.

Improvements in the infrared sensor

Several improvements have been made in the infrared sensor originally designed by Lewis. These include the acquisition of a liquid-nitrogen-cooled InSb infrared detector (Barnes Engineering), improved amplifier design, and the construction of interface circuitry to permit direct conversion of reflected pulse heights into digital form for entry into the computer. Lingel completed these improvements during the summer of 1972, and collected sample data on a variety of refuse samples. Ahmad [26] then used these data to develop a new, branched, sorting algorithm (see figure 20). Referring to the left-hand branch of figure 20 for nonmetal objects, the flow diagram shows a sequence of sorting operations, each one of which represents the execution of a linear separation algorithm identical to the kind first used by Lewis. The difference between Ahmad's algorithm and Lewis' algorithm is that instead of using one set of sorting parameters to separate simultaneously into all categories, one first selects objects belonging to the category "cellulose", then looks for items which are "glass", and so on.

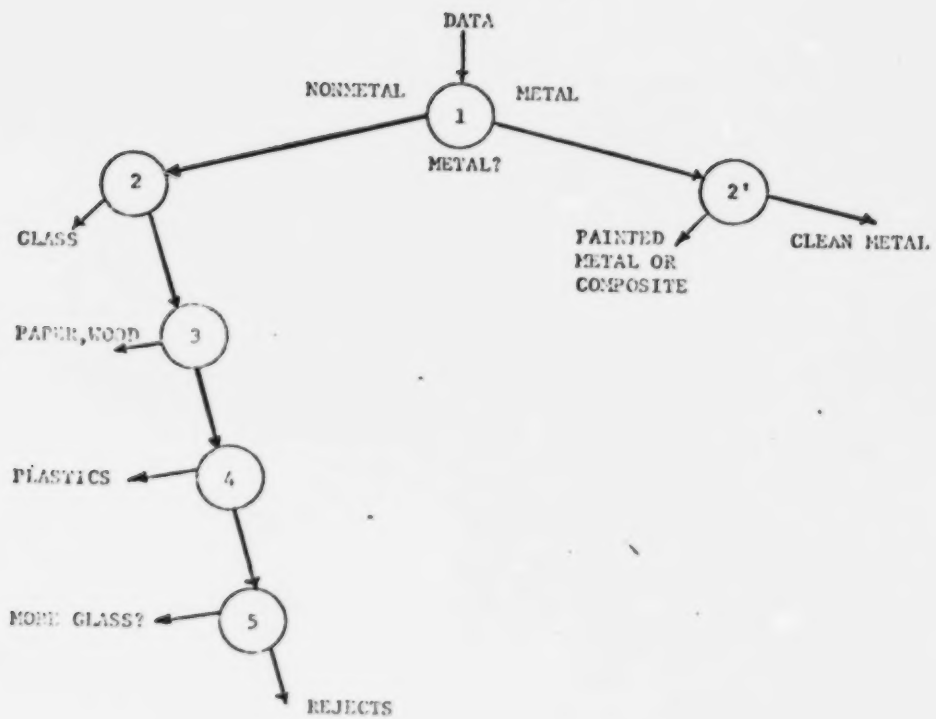
The virtue of this method is that it is much easier to separate plastic and glass from one another if the cellulose category has first been eliminated from consideration.

Lingel also installed a binary metal detector (Farmer Electric Products) for improved detection of metallic objects, and built a simple computer interface with which a single bit of information (metal: YES or NO) could be read into the computer. Based on this input bit, it was possible to sort metallic from nonmetallic objects without relying only on the infrared spectrum, and it was further possible to differentiate between clean metals and metals with paint or other coverings on them (see figure 20) using yet another linear-separation step.

Lingel's assembled system, including the infrared sensor, the metal detector, and Ahmad's sorting algorithm, represented the first fully operational bench version of the large-item sorter. Objects placed in the infrared beam and near the metal detector caused the teletype to write out the designated category. The computer programs for this process are documented in Lingel's final report [22] and in Ahmad's final report. [26] Success with the Lingel/Ahmad version was in the 50% correct range, with glass being the source of the most consistent errors.

Rodgers [27,28] made a systematic study of the operating characteristics of the Lingel/Ahmad system. He first examined the variation in the relative intensities of the four wavelengths as a function of angle away from the specular or mirror-reflection angle of various materials. Figure 21 illustrates how light is reflected from a non-polished surface, with some intensity directed along the specular direction, but with additional intensity broadly scattered about the specular direction. This diffusely scattered light contains spectral information about the contents of the reflecting surface. For example, the angular variation of the light reflected from polystyrene in figure 22 shows that at zero angle, the specular direction, the relative intensities of the four wavelengths are roughly constant, but as the direction varies away from the specular direction, one line (at 3.4 microns) is much weaker than the other three. This weaker line corresponds to a characteristic absorption in carbon-hydrogen chemical bonds, and can be used to identify materials containing such bonds.

Because of the angular variation of the spectral intensities from most materials (glass is a particularly difficult material in this regard), Rodgers modified the optical alignment of the Lingel system to guarantee that for typical object positions within the cart, the specular reflection would miss the collection



Circled computational steps are executed in sequence until a classification is found

FIGURE 20 ADMAD'S ALGORITHM FOR SORTING BASED ON THE INFRARED SENSOR AND METAL DETECTOR

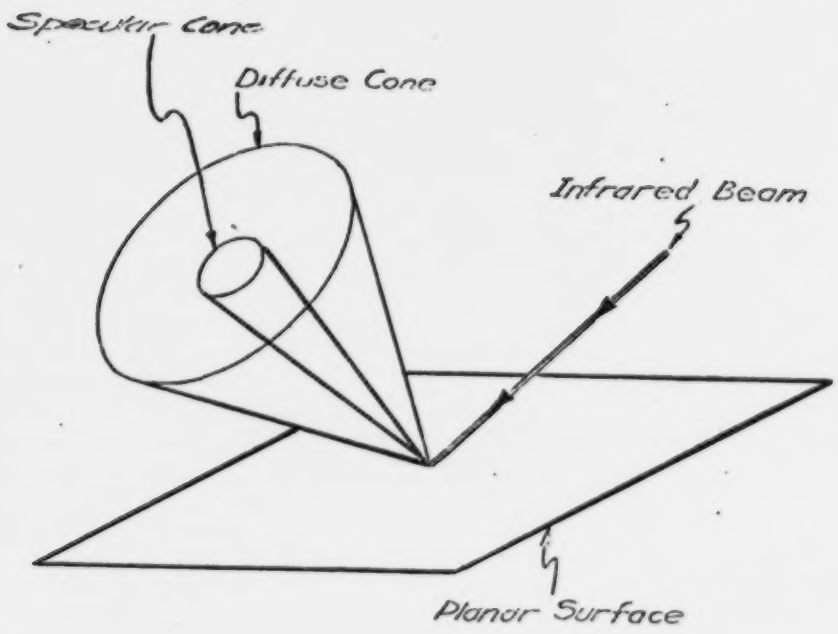


FIGURE 21 SPECULAR AND DIFFUSE REFLECTION FROM A SURFACE

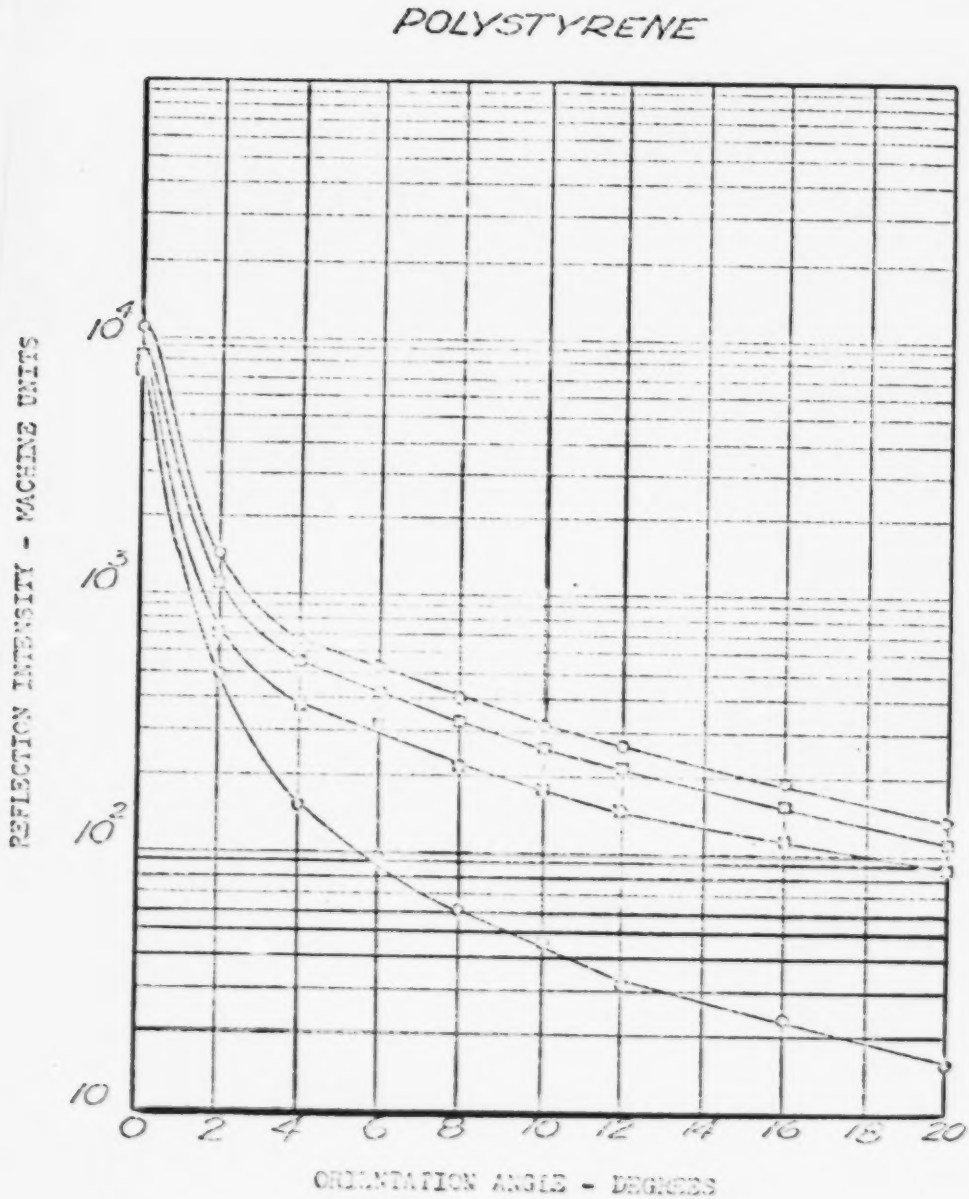


FIGURE 22 VARIATION OF THE REFLECTION INTENSITY WITH ANGLE FROM POLYSTYRENE AT FOUR WAVELENGTHS

mirror detector, thus guaranteeing in turn that only diffusely reflected light would reach the detector (see figure 23).

Rodgers also developed a calibration procedure whereby corrections for variations in the temperature of the infrared source, or drifts in relative intensities due to filter or mirror contamination, could be corrected. After all these modifications, Rodgers once again collected reflection data from a set of typical samples, and used the pattern-recognition algorithm to develop new parameters and a new sorting program (figure 24). With problems from specular reflections eliminated, Rodgers found that he could return to a single sorting matrix for each branch (metal or nonmetal). Rodgers also developed the necessary logic steps to control the writing device which would write the classification code on the cart containing the object under examination, and further improved that logic so that the program could handle more than one cart simultaneously. With this improved system, Rodgers collected the data of table 2 showing how accurately his modified system was able to sort test samples. Notice that except for glass, where the accuracy is in the 50-percent range, recognition of major categories is excellent.

The final modification by Rodgers further improved the performance on glass. The program now calculates a classification every time the filter wheel rotates once (20 milliseconds). At the cart speeds used in the system, 20 milliseconds corresponds to a new spectrum every 1/4 inch. A record is kept of each classification. After the object passes out of view, the category which occured most often is declared "the category" for that item. With this improvement, glass, which had been incorrectly classified because of erroneous specular reflections from the leading edge of the object, became as accurately classified as the other objects. Thus, the system now is capable of nearly perfect classification of cellulose, plastics, glass and metals.

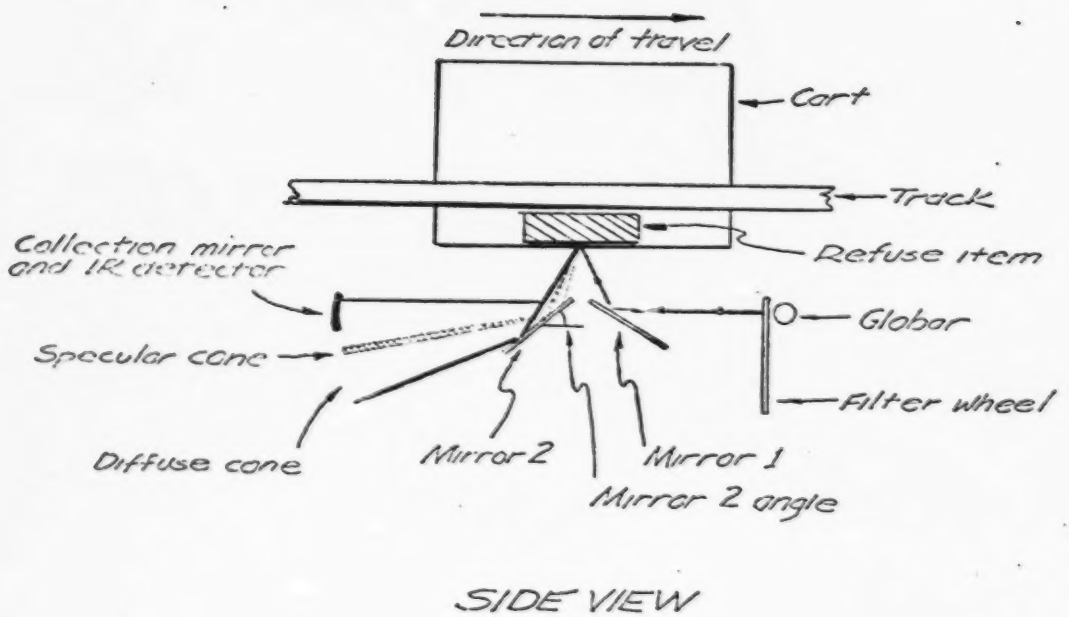
Plant assembly

During the summer of 1973, final assembly was made of a prototype large-item sorter. The sensors were installed beneath the track and the computer was connected both to the sensors and to the code-writing device. Items were dropped into the carts from a feed conveyor, the carts carried the items over the sensors, the computer controlled the code-writing device, and code-reading devices activated dumping mechanisms. Operation of the prototype was filmed to maintain a record. Television films were also made by Station WBZ-TV (channel 4 in Boston, an NBC affiliate). The

TABLE 2

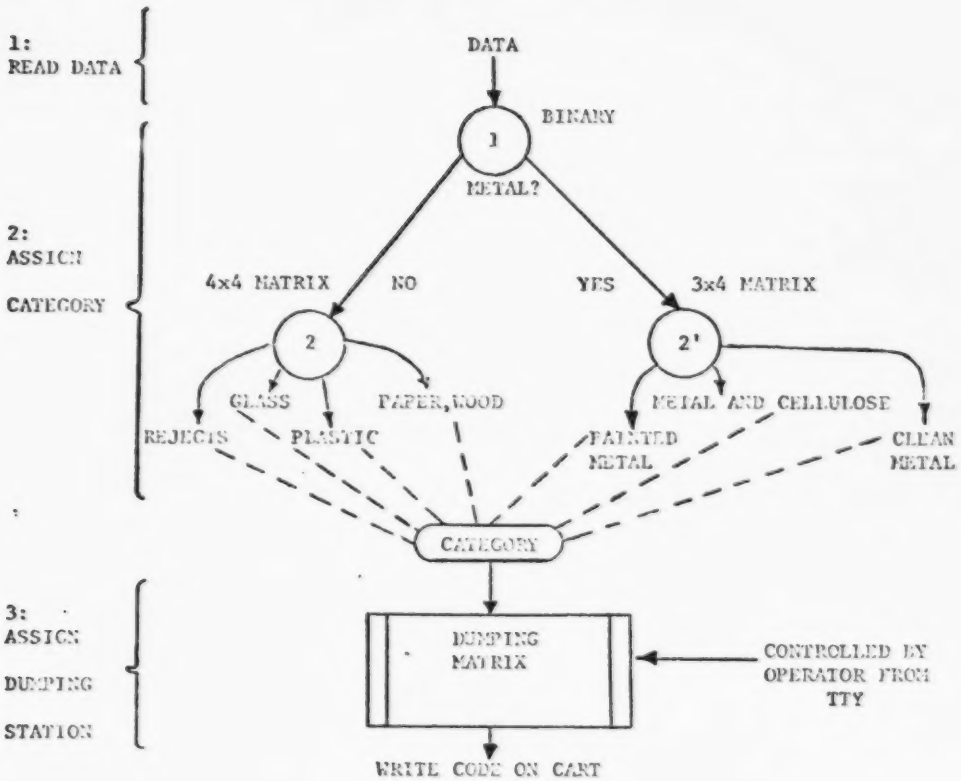
Performance record of the large-item sorter using a single infrared spectrum

ITEM	PROPER CLASSIFICATION	% ACCURACY
Plastic Bleach Bottle (no paper label)	Plastic	96
Butter Container	Plastic	95
Garbage Bag (wrinkled)	Plastic	90
Styrofoam Steak Container	Plastic	98
Clear Soda Bottle	Glass	65
Colored Soda Bottle	Glass	45
Glass Jar	Glass	73
Wrinkled Newspaper	Cellulose	100
Damp Newspaper	Cellulose	100
Juice Carton	Cellulose	100
Magazine	Cellulose	100
Damp Magazine	Cellulose	100
Cotton Clothing	Cellulose	100
Block of Wood	Cellulose	100
Aluminum Can	Painted Metal	100
Steel Can	Painted Metal	100
Steel Can (on bottom)	Painted Metal	87
Wrinkled Aluminum Foil	Painted Metal	100



The spectual reflection is directed away from collection mirror

FIGURE 23 MIRROR ARRANGEMENT FOR THE INFRARED SENSOR



The plant operator can control where each output category is to be dumped from the teletype console.

FIGURE 24 RODGERS' ALGORITHM FOR SORTING AND PLANT CONTROL BASED ON THE INFRARED SENSOR AND METAL DETECTOR

sensors and carts operated satisfactorily, with sorting accuracies consistent with the results of table 2. Following film documentation of the operation of the assembled system, the large-item sorter was shut down, primarily because the prototype plywood carts were reaching the end of their useful lives.

SUGGESTIONS FOR FUTURE DEVELOPMENTS IN THE INSTRUMENTATION SYSTEM

The instrumentation system has been proved sufficiently on a laboratory and prototype scale. It is now ready for pilot-scale testing on real municipal refuse. As such a pilot-scale test proceeds, several areas may require improvements. These include:
a) the effects of wet garbage on the sensors, and as a contaminant;
b) the performance with inhomogeneous objects -- these may require a modification of the computer program such that if two categories receive a significant number of votes while an object is being scanned, then the object is declared inhomogeneous and is rejected; and
c) the impact sensor, which is still in the laboratory-test stage.

One way to handle the wet-garbage problem would be include an additional infrared wavelength which would be sensitive to moisture content. In this way, dry cellulose (paper) and wet cellulose (garbage) could be differentiated. Some wet paper may be sorted as garbage, which would be wholly acceptable for most purposes.

Contamination of the optical components or the carts may require periodic automatic cleaning. The effects of a buildup of contaminants on the infrared optical components would have to be studied as part of a pilot operation.

There is room for considerable improvement in the level of sophistication of the computer programs, and in the number of output categories being identified. The useful limit on the number of output categories has not yet been reached -- it could conceivably be as high as fifty or more. Further study of actual rubbish, and relations of these studies to progress in the secondary-materials industries, will be needed in order first, to identify useful materials, and second to devise improved sorting algorithms for selecting those materials from the refuse stream.

CHAPTER 5

VORTEX CLASSIFICATION OF SMALL PIECES

A device has been constructed which has classified particles according to density by allowing them to fall through an air vortex flow field and to change radial position under the influence of aerodynamic forces.

PURPOSE OF CLASSIFIER

The vortex classifier was designed as a means of handling the small items either passing through the vibrating screen in the "presorter" section of the process, or those leaving the hammer mill after rejection by the large-item sorter. Most existing air classifiers are binary - that is, they are capable of dividing an input stream into lighter and heavier pieces (eg the zig-zag classifier [29]). Use of such classifiers has two disadvantages for a plant of the proposed type. Firstly, a relatively large number of separate but connected classifiers is required to achieve relatively homogeneous streams in desired categories. Secondly, there is difficulty involved in changing the product streams in response to market conditions: the product streams have virtually to be decided upon when the plant is designed.

A multi-output classifier which does not have these disadvantages is the ballistic separator,[3] in which particles are ejected from a rotor and divide themselves among a number of hoppers as they fall, the denser particles going to the furthermost hoppers. This has the potential of being capable of adjustment to change the product qualities, but the virtually uncontrolled nature of the flow and the low aerodynamic forces involved result in only crude separation.

PRINCIPLE OF OPERATION

A fluid vortex is defined as radial flow towards a sink with rotational flow superimposed. In the absence of guide vanes or other means of imposing torque of the fluid in the vortex, a so-called "free" vortex, that is, one having constant angular momentum and therefore with the angular velocity inversely proportional to radius, will be obtained. In unconfined free vortices, such as tornadoes, there is additionally a large axial-velocity component in the low-pressure vortex core.

Confined vortices are frequently used to separate out particles in gases and liquids, or to produce "light" and "heavy" fractions. Early in the present work it was determined analytically that the shape of the confining chamber could be made so that particles could take up equilibrium radii. [30] Furthermore, the equilibrium would

be stable: that is, if the particles were disturbed from their equilibrium radii, they would tend to return to them.

The path a particle takes in approaching its equilibrium radius has been found to be a unique function of the density, and to a lesser extent of the drag coefficient, of the particle. The principle of the classifier is, then, that particles are injected into a fluid vortex of certain characteristics; that the particles spread out along varying paths as they approach their equilibrium radii, the paths depending largely on the density of the particles; and that they are collected at convenient points along these separate paths.

NOTE ON PAST WORK

As noted in the report of the first contract period, [10] the original intent was to inject either a batch or a steady stream of particles into the vortex classifier, to allow the particles to attain equilibrium radii, and then to collect them at these radii. Two phenomena prevented operation in this mode. The casing boundary layers were found to be more influential than had been predicted, and distorted the path of each particle considerably. And there was found to be considerable overshoot of particles injected at other than their own equilibrium radii or angular velocities.

The problem of the casing boundary layers was avoided by arranging for classification to take place while the particle fell under gravity from the injection point to the boundary layer on the lower surface (this assumed that the transverse plane of the classifier was horizontal).[31]

The transient paths of a range of nonequilibrium particles injected at various radii and velocities were predicted in a simple computer program (figure 25), and these paths were confirmed by multi-exposure-flash photography (figure 26). It was obvious that better separation would be given by operating in the transient rather than the equilibrium mode, and this procedure was adopted.[31]

EQUILIBRIUM IN A VORTEX

According to Newton's laws of motion, a particle continues in a straight line unless acted upon by an external force. If

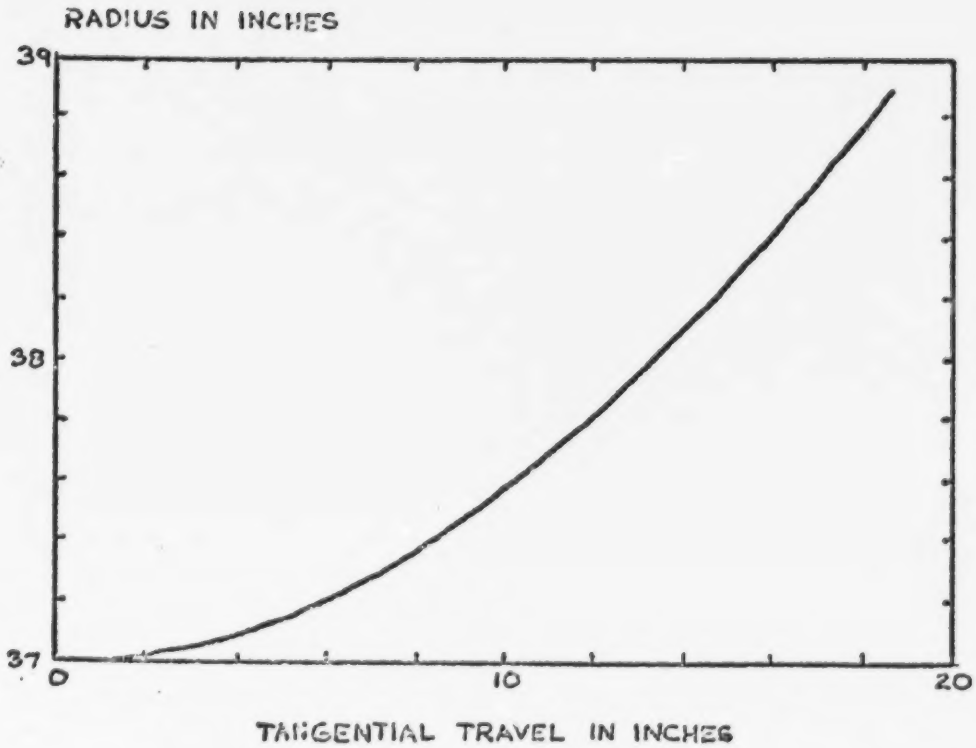


FIGURE 25 COMPUTER PREDICTION OF PARTICLE MOTION IN VORTEX CLASSIFIER

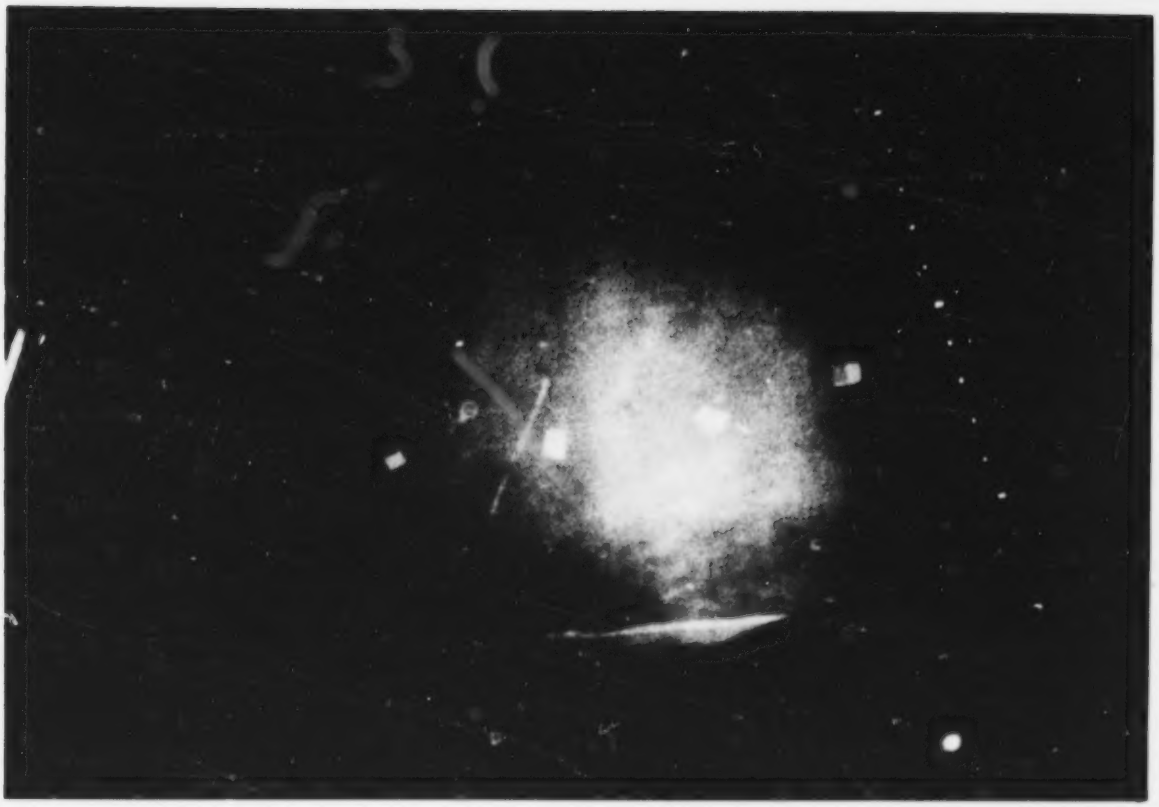


FIGURE 26 MULTIEXPOSURE FLASH PHOTOGRAPH OF PARTICLE

an external force acts on a particle it will impart an acceleration to the particle in the direction of the applied force.

The velocity components of the fluid in a vortex can be considered separately. The tangential component of velocity (Co) acting on a particle in a vortex will tend to accelerate the particle tangentially to approach the local tangential velocity. The particle would continue in a straight line and leave the vortex tangentially if it were not for the force imparted from the fluid drag of the radially-inward component (Cr). This drag curves the path of the particle towards the center.

Whether the particle goes to the center or to the outside depends on the relative magnitude of the radial drag. In equilibrium, the particle would travel around the vortex at the same tangential velocity as the local flow component, and would experience only a radially inward flow. The inward drag from this radial flow would impart an inward acceleration, and if this were equal to ($C\theta^2/r$) the particle would travel in a circular, stable path.

Adjustment of the magnitude of this radially inward flow without coupling to the tangential flow is possible in a confined free vortex simply by appropriate contouring of the walls. This contouring changes only the radial component of velocity, because the tangential component, after initial setting by, for instance, guide vanes at entry to the vortex, is inversely proportional to radius without regard to the shape of the walls. [10]

EXPERIMENTAL WORK

Tests carried out in the M.I.T. air vortex classifier and parallel computer predictions of particle paths are reported by McCarthy. [31] A range of geometrical shapes - spheres, cubes, lamella or various thicknesses, - sizes, and densities of particles was injected into the air classifier at mean radius and at the velocity and direction of the local component of tangential velocity. The transient paths of the particles as they approached their equilibrium radii were recorded by means of multi-exposure stroboscopic flash photography (figure 26). These paths were compared with computer predictions based on calculations of particle motion under the influence of simple aerodynamic drag in a two-dimensional axisymmetric vortex. A sample of the results is shown in figure 25.

Very good agreement between experiment and computer prediction was obtained for all but very thin lamellar particles for which in any case the drag coefficient was uncertain.

PREDICTIONS OF FULL-SCALE PERFORMANCE OF VORTEX CLASSIFIER

Two distinct ranges of operation of vortex classifiers are anticipated: for lighter-than-water materials such as plastics, woods and paper products; and heavier-than-water materials such as nonferrous metals and glass. In the first group air would be the classifying fluid, and water would be used for the second.

Predictions of the classifying performance are shown in figure 27. The particle paths are illustrated in figure 28. Separation in the transient mode is sufficiently rapid for several streams of particles to be handled in a single vortex. Power costs per ton should be a very small fraction of the potential value.

NEEDED WORK

The principal uncertainty in predicting the usefulness of the vortex classifier is the unknown effects of various particle shapes. One possibility is that shapes will be so random that only crude separation by density will be possible unless some pre-treatment, such as pelletization, is adopted. A second possibility is that particle shape will be a characteristic of material and that separation might therefore be assisted. An investigation of the effects of realistic, rather than idealistic, shapes is therefore required.

The design of an injector capable of imparting a consistent velocity and direction to the feed particles is needed. The effects of various designs of collection scoops on the fluid flow should be studied. A prototype of optimum design should then be constructed and its performances determined under various throughputs.

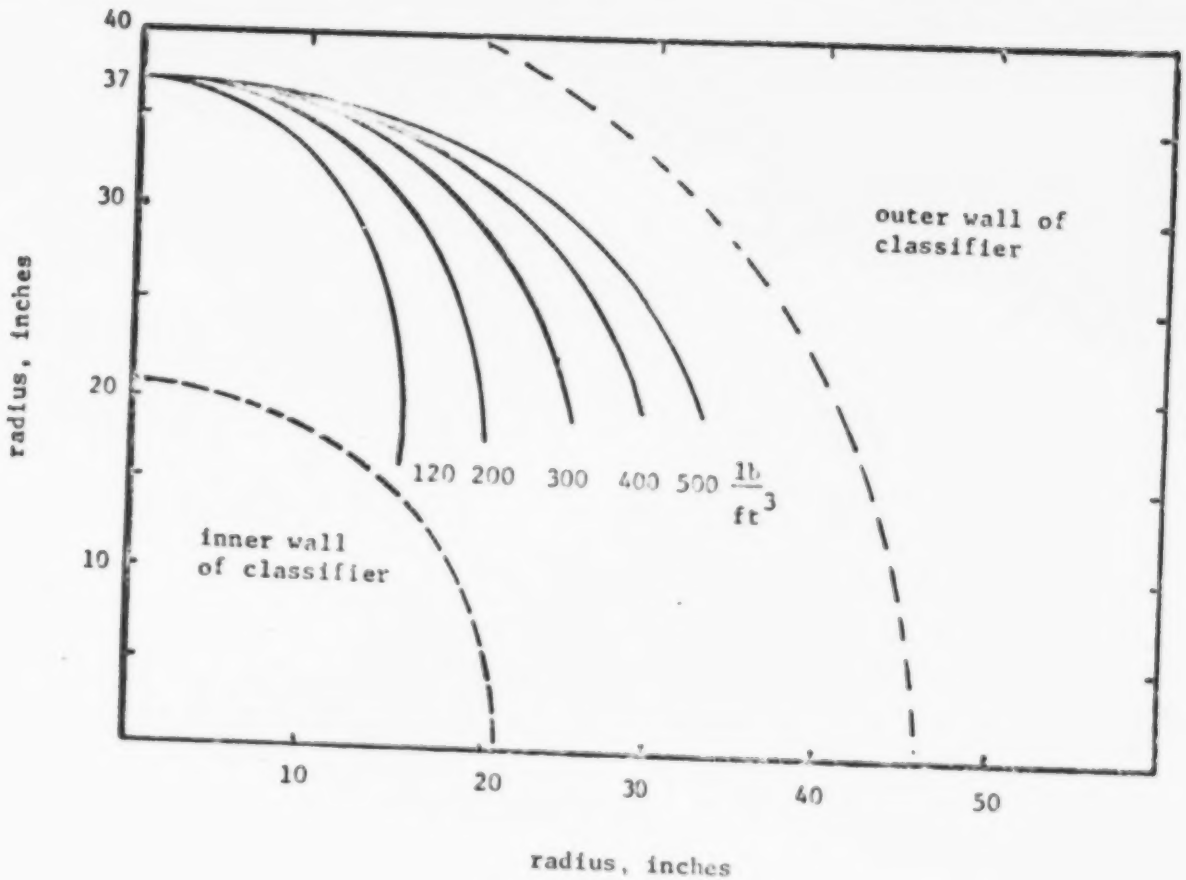


FIGURE 27 COMPUTER PREDICTIONS OF VORTEX CLASSIFICATION OF NONFERROUS METALS IN WATER

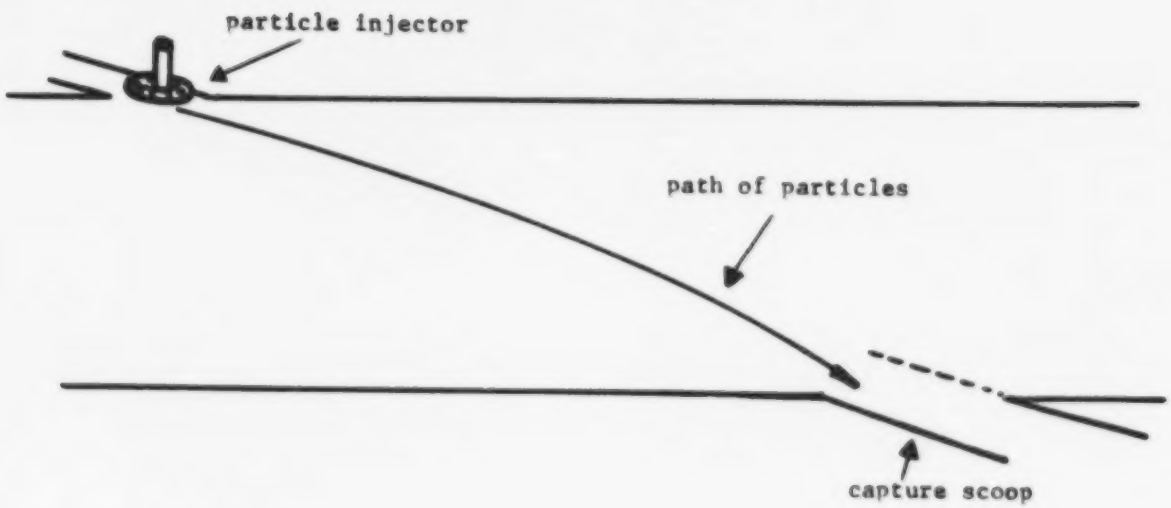


FIGURE 28 PARTICLE PATHS IN VORTEX CLASSIFIER

CHAPTER 6

EXPERIMENTS ON AIR CLASSIFICATION AND DESIGN OF A UNIT

Observation of typical refuse, backed up by the data described in chapter 2, indicates that a large proportion by volume of municipal refuse consists of loose pieces of paper and plastic. The proportion by mass was found to be 12.5 percent in one large sample (550 lbm) and for general municipal refuse the mass-proportion might be expected to vary between ten and twenty percent.

These loose pieces have generally low recycle value. They tend to be contaminated, both because they are loose and because the first use in many cases was for wrappings. And as a category these materials are too heterogeneous to have a significant reclaim value. In the mixed condition the most likely use is as a fuel. Separated into plastic and paper categories (by, for instance, the Bureau of Mines electrostatic method[32]) a slightly higher market value is possible for uses such as fillers and low-grade moldings, and for roofing papers.

If these loose pieces were to be left in the stream, they would have a strongly negative value as contaminants.

Therefore it is desirable to remove loose pieces of paper and plastic film at an early stage. In the M.I.T. process, it was elected to design for removal by air suction over the vibrating screens in the so-called presorter. Some simple experiments were carried out to determine the dynamic pressures required, and a design study was completed.

AIR-CLASSIFICATION EXPERIMENTS

The reason for the experimental work was as follows. While it is easy to find the fan dynamic pressure and flow required to lift a given piece of material lying at a known attitude, it is not presently possible to predict how much blockage can be tolerated in front of a fan before reversed, stalled, flow begins to expel some previously lifted pieces; nor is it possible to predict that flat, horizontal pieces will not turn to assume a low-drag, vertical, position and in this way to drop back.

A simple test rig was made by Hutchison and Raskob.[33] It consisted simply of a vertical, open-ended plywood box of four-foot sides, with a horizontal low-blockage horizontal

wire mesh at the lower end and a 42-inch-diameter axial fan, with the disk horizontal, at the upper end (figure 29). The fan was controlled by louvers, and an air-straightening honeycomb was used, together with a capture screen, below the louvers.

The tests first established air-flow patterns, using a pitot tube and smoke tracers, through the chamber with the fan unblocked and with various amounts of blockage (by sheets of paper) at inlet. Second, the tests determined what densities of sheet material would be lifted with various fan airflow rates. Third, stroboscopic photographs were made to show film behavior during the lifting process from the lower screen to the upper screen. These are fully reported by Raskob [33] and are summarized below.

The airflow tests showed that intense vortices, which had been thought to be a possible harmful manifestation because of the presence of struts, angles, foundations and so forth, were not present to a degree which could cause difficulties in lifting sheet materials. However, one vortex which was almost unavoidably present, did cause some sheets to rotate or fold during lifting.

The airflow was such that, with an unblocked fan, 19 or 20 sheets of 16-lbm typing paper, stuck together, could be lifted repeatedly. The mean air flow at the lower screen was reduced by upper-screen blockage, as shown in figure 30. Single sheets would still be held at the upper screen when the blockage was 90 percent. At above 95-percent blockage, one or another piece of paper would fall whenever an attempt was made to fill the remaining unblocked area. At this point the total air flow would be too low to lift anything but tissue from the lower screen.

The stroboscopic studies of paper motion, figure 31, showed that most horizontal sheets remained approximately horizontal during lifting. Some rotation of sheets took place when the upper screen was blocked in the area over the sheet, because of the induced vorticity. The time taken for the sheets to travel from lower to upper screens was within 20 percent of the undisturbed-air-movement time. This applied to cases where the upper screen was up to 50-percent blocked.

Sheets were chosen as a worst case in these experiments. Crumpled pieces are not susceptible to the changes of attitude and drag coefficient which sheets can produce when turned.

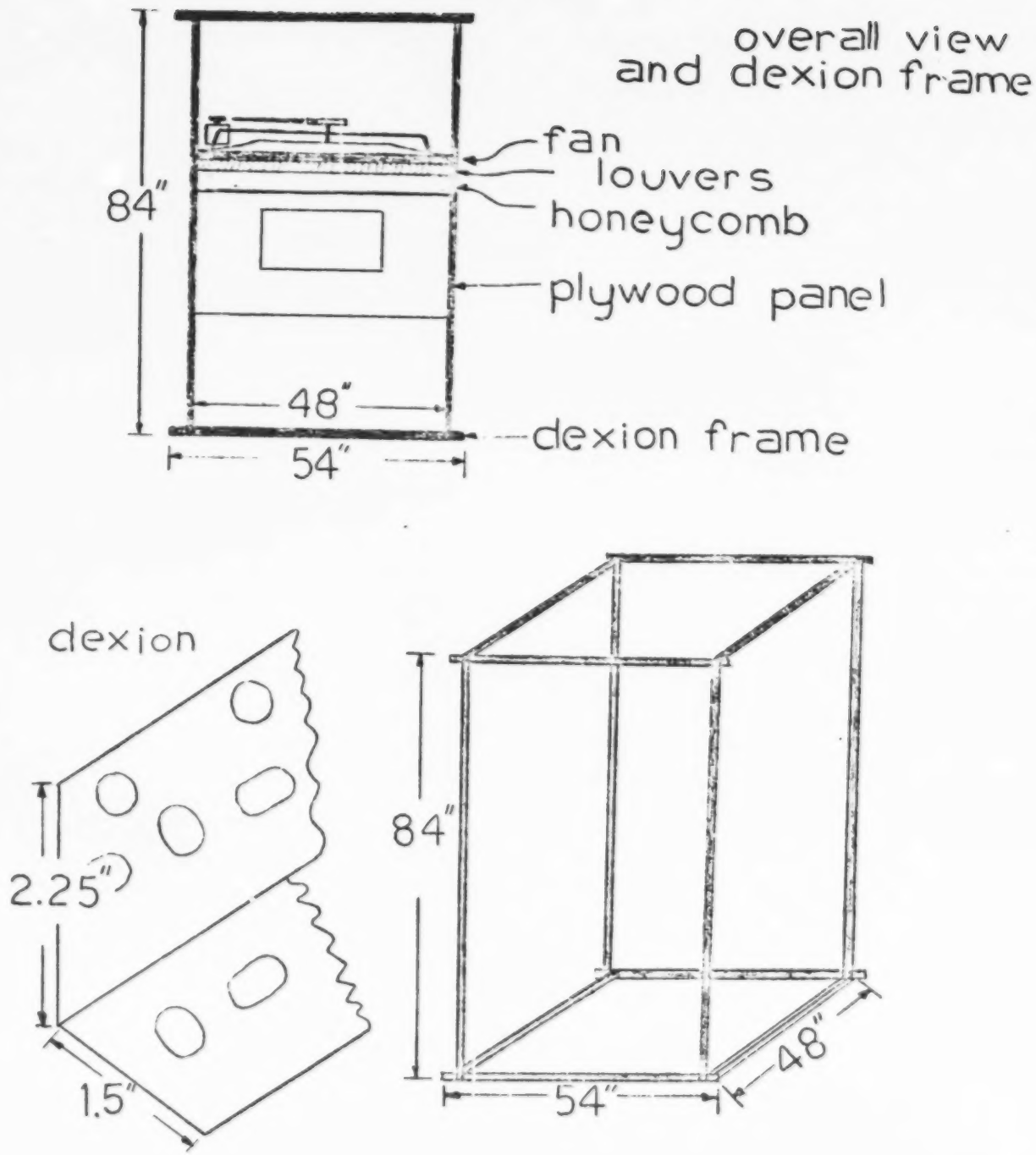


FIGURE 29 AIR CLASSIFICATION TEST RIG

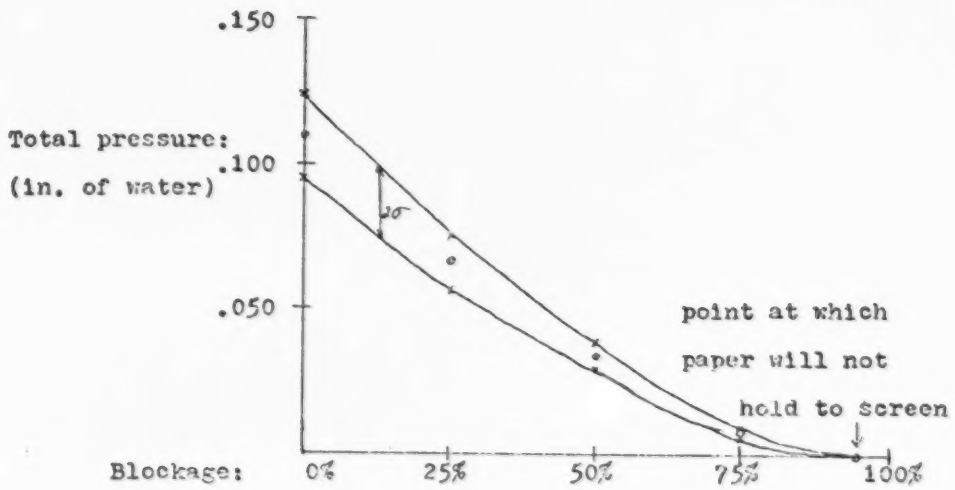


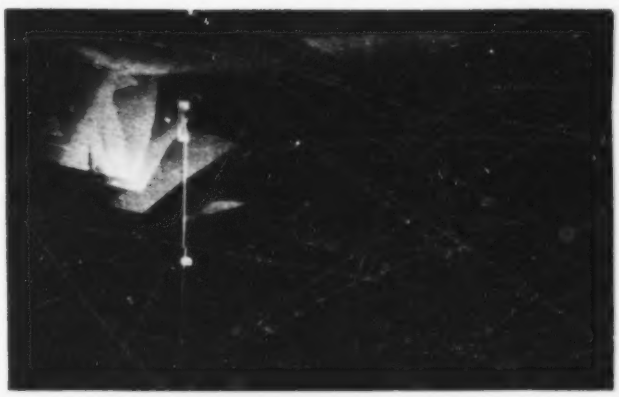
FIGURE 30 EFFECT OF SCREEN BLOCKAGE ON SUCTION PERFORMANCE

AIR-CLASSIFIER DESIGN

The experiments established some useful criteria for the design of a full-size classifier for the pilot plant. A vertical air-flow velocity of ten to twelve feet per second at the lower screen in its unloaded condition would be used. The upper screen would be moved at such a speed that in the worst conditions of maximum feed rate to the lower screen, with maximum loose-paper content, the blockage would be less than 50 percent.

An endless-belt nylon screen passing over two rollers and enclosing the fan was the chosen configuration. This configuration was compatible with a number of alternative methods of treatment of the lifted fraction. Initially it was intended to scan the belt with an oscillating infrared reflectance sensor (similar to those described in chapter 4), and to remove plastic pieces by operating selected air jets. This principle of binary separation is used in automatic ore-separation machinery. [34] The recent development of the Bureau of Mines electrostatic plastics-paper separator [32] seems to offer promise, and would be easily adaptable to the proposed configuration. And, of course, it is always possible to remove the lifted fraction as a mixed plastics-paper mixture suitable for burning.

A cross-section of the design is shown in figure 32.



A: FOUR SHEETS OF PAPER PLACED ACROSS BACK OF TRASH SCREEN

B: FOUR SHEETS OF PAPER PLACED ACROSS CENTER OF TRASH SCREEN

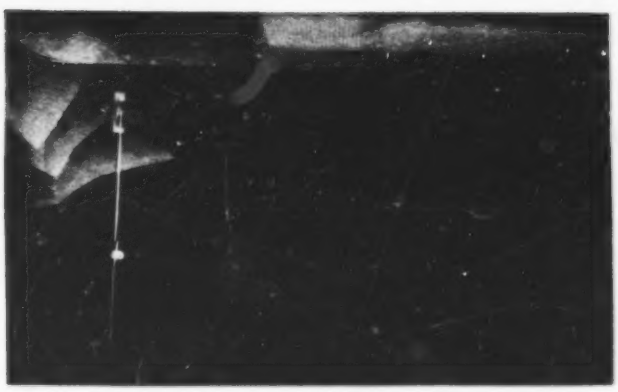


FIGURE 31 MULTIEXPOSURE FLASH PHOTOGRAPH OF LIFTING OF PAPER SHEETS

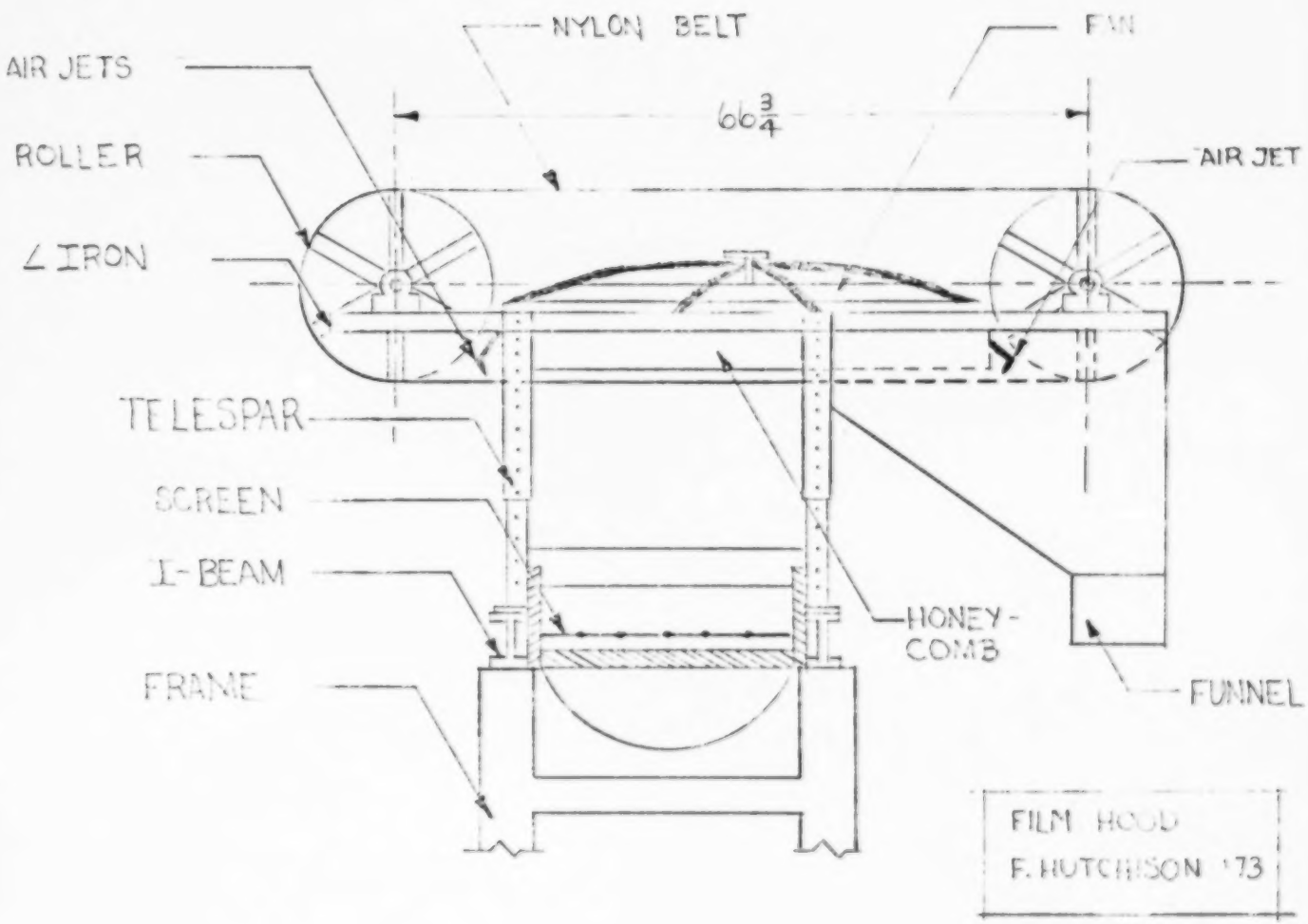


FIGURE 32 PRELIMINARY DESIGN OF TRAVELLING-MESH BELT FILM-REMOVAL HOOD

CHAPTER 7

PREDICTED COSTS AND INCOME

Cost and income predictions, especially when made by the proponents of a process, are always suspect. To show the attractiveness of the proposed process it would be easy to list all apparent capital and operating costs and the expected income and to show an extremely favorable profit figure. With this type of accounting there is always a strong suspicion that many expenditures have been omitted. We believe that a preferable approach is to compare the capital and operating costs of other types of refuse-treatment plants to evaluate the differences in costs.

CAPITAL COSTS

The principal reason for this approach is that there are certain major site costs, roadways, receiving areas, weighing stations, offices and the like which will be common to all types of central-station facility. For plants in the size range of 500 to 2000 tons per day (TPD), these first costs have been found (from known costs of incinerators and compaction transfer stations) to be between $1000 and $3000* per TPD capacity, depending on real-estate costs in particular locations and on the architectural embellishments of the buildings.

We shall estimate for a conservative value of $3000 per TPD and calculate for a 1000 TPD (two-shift basis) plant.

For high-pressure compaction plants the additional "machinery" costs are in the range of $200 - $800 per TPD. The total costs of the Reclamation Systems Inc. plant in Cambridge, Massachusetts were about $3 million for a 2000 TPD capacity, and these costs were much higher than anticipated because of special site problems, long strikes by contractors, and the first-ever production of the refuse-baling press by the manufacturers, the Lombard Company. This figure could be broken down into $1000 per TPD for site, buildings and facilities costs, and $500 per TPD for the two presses and the feeding and discharge arrangements.

Total first costs of incinerators are higher, from $10,000 to $20,000 per TPD capacity, reflecting the large first costs of the furnaces, controls, air-pollution-control equipment and stack.

*Cost inflation at a rate of up to 1.5% per month has occurred since early 1973 when these figures were proposed.

In comparison with incinerators and presses, a plant using the presently proposed sorting processes will have a variety of lighter and less-expensive equipment. A process computer, probably handling billing and other accounting in addition, will cost on the order of $20,000 (the prototype basic version was $4000). There will be about 30 sensors, costing an average of $1000 each; perhaps 20 baling presses for the product output, costing $20,000 each; a small hammer mill for heterogeneous items, costing perhaps $50,000 including drive and controls; a vibrating screen costing about $20,000; the multi-lane cart system, which will be custom-designed from standard components - we believe that $100,000 should be conservative; an overhead belt magnet, for $10,000; a film extractor and fan, $10,000, and miscellaneous extras.

Computer	$ 20,000
Sensors	$ 40,000
Baling presses	$400,000
Hammer mill	$ 75,000
Screen	$ 25,000
Cart system	$100,000
Belt magnet	$ 25,000
Film extractor	$ 25,000
TOTAL	$710,000
CONTINGENCIES	$290,000

TOTAL MACHINERY COST $1,000,000

ESTIMATED SITE COSTS $3,000,000

TOTAL PLANT FIRST COST $4,000,000

The total salvage value of the site, buildings and machinery at the end of 10 years is assumed to be $1.5 million in constant dollars. The net daily amortization costs at 8 percent interest then amounts to about $1650 (based on a 300-day year).

Daily cash flow

We shall assume that the plant is located in what is recommended as a minimum-disposal-cost area where the costs of disposing of the uneconomic fraction and the credit received for the processing of the incoming refuse equal $6 per ton. If these costs and credits were $10 or more per ton, as is the case in many urban and suburban areas, the cash-flow balance would be even more favorable.

We are also assuming low prices for the sale of the potential products. For instance, we list paper at $10 per ton, yet clean newspaper is presently (late 1973) fetching $80 per ton, FOB west-coast ports. Glass is included in the material being sold at $10 per ton, yet color-sorted glass realizes $20 per ton at glass-manufacturing plants and, at bottlers, about $100 per ton as brand-sorted, undamaged bottles. We have also tried to be conservative in the number of employees (10 per shift) and the average earnings. Nonferrous metals, of value from $200 per ton for aluminum to $400 per ton for copper, are conservatively included in the $10-per-ton average value of the recoverable fractions.

Daily costs for 1,000 TPD plant

Amortization	$1650
Labor - 20 employees 8 hours, $10 per hr.	$1600
Disposal costs, 300 tons, $6 per ton	$1800
Utilities, insurance, taxes etc.	$ 450
	$5500

Daily income

Ferrous metals 100 tons @ $10	$1000
Paper 300 tons @ $10	$3000
Other large items 150 tons @ $10	$1500
Small items 150 tons @ $5	$ 750
Processing fees 1000 tons @$6	$6000
TOTAL INCOME	$12,250
DAILY SURPLUS	$ 6750

Annual surplus (profit) - 300-day year
$2,025,000

Costs per sort

If all the plant costs per day ($5500) are ascribed to the large-item sorter, which sorts 4500 large items per ton, and handles an input of 1000 TPD, the cost per sort is:

$$\frac{\$5500 \times 100 \text{ cents}}{4500 \times 1000} = 0.122 \text{ cents per sort}$$

A more realistic figure might be 0.08 cents per sort because of the considerable proportion of the input stream which is handled by the magnetic belt, the film extractor and the vortex classifier. This sorting cost, updated for current conditions, would be a guide to the manager of a plant when he chooses among alternative sorting strategies in his day-to-day adjustment of the sorting criteria.

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